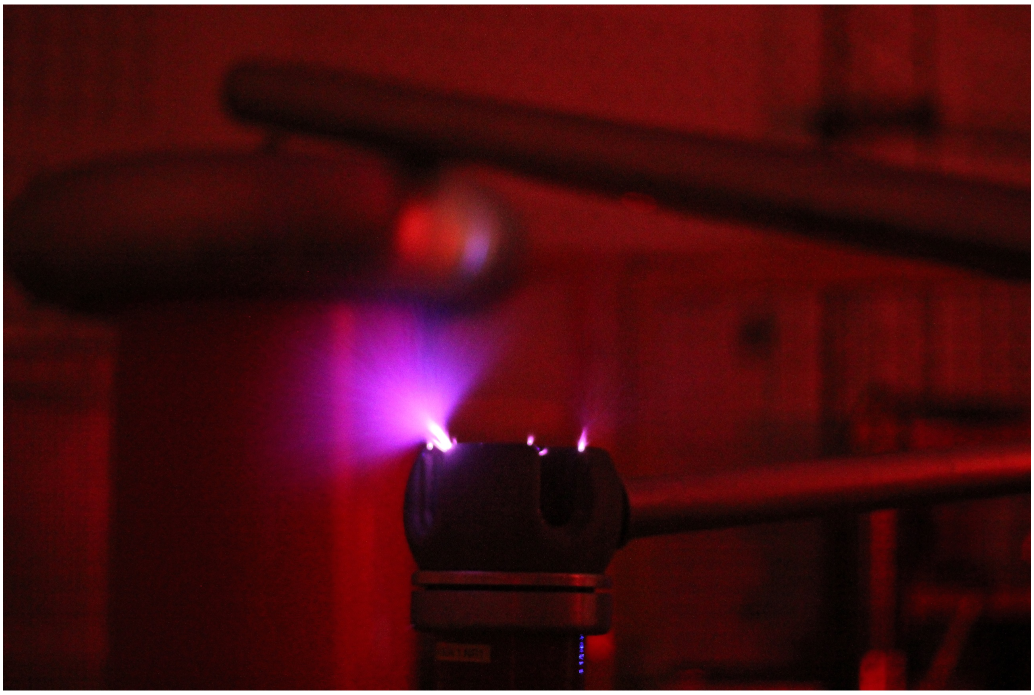
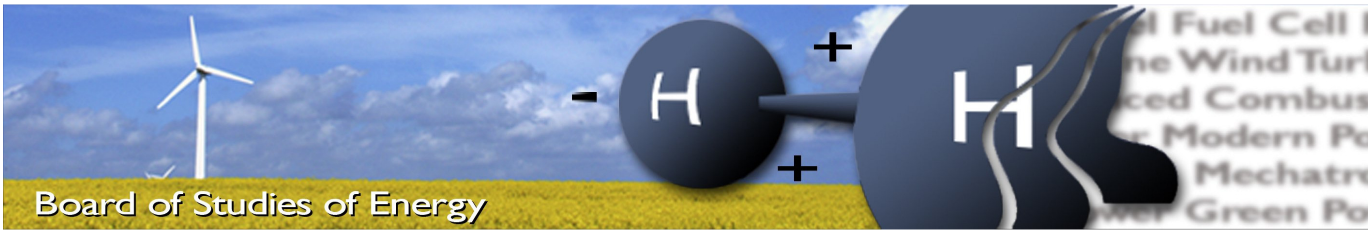
Electric field optimization to reduce corona in AAU/ET's 200 kV High Voltage laboratory setup



MASTER'S THESIS, AUTUMN 2013
GROUP EPSH4-1033
BOARD OF STUDIES OF ENERGY

AALBORG UNIVERSITY
STUDENT REPORT



Title:	Electric field optimization to reduce corona in AAU/ET's 200 kV High Voltage laboratory setup
Semester:	10th
Semester theme:	Master's thesis
Project period:	01.04.2013 to 12.09.2013
ECTS:	30
Supervisor:	Claus Leth Bak
Project group:	1033

SYNOPSIS:

The aim of this thesis is to investigate if the amount of corona in the high voltage laboratory setup can be reduced. The report will include a detailed study on the electrical field strength in air. Finite element models studying the electrical field distribution for the high voltage setup. The setup will undergo a series of partial discharge tests to determine where on the setup corona is present, how intense and what the corona onset voltage is. The FEM program is used to validate the PD measurements performed at the laboratory. A new component for the setup is designed and constructed in the workshop. New partial discharge measurements are conducted to see if the new component has any effect on the corona present in the setup.

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Bjarni Helgi Þorsteinsson

Copies:	2
Pages, total:	63
Appendix:	6

By signing this document, each member of the group confirms that all group members have participated in the project work, and thereby all members are collectively liable for the contents of the report. Furthermore, all group members confirm that the report does not include plagiarism.

Preface

The aim of this thesis is to investigate if the amount of corona present in a 200 kV setup in the high voltage laboratory at Aalborg university can be reduced. Either by creating a corona screen or by replacing parts of the setup.

The electrical field strength will be examined in detail, both on the laboratory setup and standard electrical examples such as a rod to plane gap. A finite element model will also be constructed, in Opera3d FEM program, of a simple electrical system to observe the behavior of the electrical field. A detailed description of what corona is and what effect an electrical field has on gasses such as air will be conducted.

Partial discharge tests will be conducted in the laboratory with Omicron MPD-600 partial discharge detector. The partial discharge tests are performed to locate where and how much corona is present in the setup along with the corona onset voltage.

A part of the setup that has the lowest corona onset voltage will be chosen for further studies. Electrical field theory calculation, and a finite element model will be constructed, of the chosen part of the setup. The part that is chosen for further studies is a connecting sphere or a connecting node. which connects the transformer to a capacitive voltage divider. The connecting sphere has some sharp edges which result in a high electrical field. It will be examined if the connecting sphere will be replaced or if a corona screen will be manufactured.

The FEM model will be used to validate the partial discharge measurements performed at the laboratory. This is done by examining the maximum electrical field in the model and calculating with the streamer breakdown criterion. This is done to examine if there is corona in the FEM model of the connecting sphere. And to validate the corona onset voltage found during the partial discharge measurements.

A new sphere is calculated and designed to have no corona at 200 kV. The sphere is then constructed at the university workshop. A second set of partial discharge measurements is then conducted to see if the new connecting sphere gives different partial discharge measurements.

Acknowledgments

I would like to thank my supervisor Claus Leth Bak for is guidance and support thought out the project period. I would also like to thank Mads Lund for his help in the laboratory.

Reading guide

The report uses the Vancouver method for citations [source number]. On the back cover of the report is a CD, where all models, test results and a copy of internet citations can be found. Pages in the appendices are numbered with roman numbers.

Contents

Chapter 1

Introduction

1.1 Introduction

When dealing with setups in a high voltage laboratory some amount of corona can be present in the test setup. Corona can produce some inaccuracies when performing measurements on high voltage equipment.

Corona is a type of partial discharge that can occur in almost all electrical equipment. The corona effect is common among high voltage lines and the effect can be detected by a loud noise where the corona is being produced and by a purple glow around the wires in question. Corona discharges happens when the electrical field strength exceeds the dielectric strength of the air surrounding the electrical equipment. What happens is that the air partially brakes down and starts to conduct electricity [9] [18].

Corona is a subcategory of a partial discharge, it is an external discharge occurring on the surface of the conducting material and in the air surrounding the material. Unlike partial discharges corona has no effect on the insulation materials or the lifespan of equipment. But both corona and partial discharges do result in power losses [16].

Corona will mainly interrupt partial discharge measurements e.g. give noise to other measurements performed and will produce erratic spark activity.

The corona will not be present in all parts of the test setup.

Corona is mainly produced on parts of the setup that has a sufficiently small radius of curvature, so that the electric field becomes to high for the air surrounding the test setup. Resulting in corona activity at that particular area.

For the available setup in the university laboratory corona discharges are known to be present on parts of the setup. The setup consists of two cascaded 100 kV transformers connected to a large coupling capacitor. The capacitor is constructed in a such a manner that it has a large curvature of radius so it will not produce any corona when energized by the transformers. There are also connected two voltage measuring capacitors, capacitive voltage divider, to the setup. The setup can be seen on figure 1.1.

Figure 1.1: The setup in the university laboratory.

In figure 1.1 the transformer is marked with a red square, the voltage divider with a green square and the coupling capacitor is marked with a blue square.

The transformer is rated to 100 kV and two of them are cascaded giving a rated output of 200 kV. Some partial discharges should be apparent on the top electrode of the transformer and possibly the connection from the transformer to the voltage divider.

The top electrode of the transformer is designed to have no corona at 100 kV, now to transformers are cascaded resulting in an output of 200kV. This is 100 % the rated output of the top electrode so some corona can be present on the top electrode. The same is true for the connecting sphere that sits on top of the capacitive voltage divider. There is no corona at 100 kV, but the connecting sphere has some sharp edges which could result in corona at higher voltages than 100 kV.

The aim of this project is to locate where corona is being formed at the available setup, and reduce it to get better partial discharge measurements.

The setup will be improved by constructing a corona shield or replacing parts of the setup in the laboratory at the university.

Partial discharge measurements will be performed to see the overall corona in the setup before and after implementing a screen, or replacing parts of the setup. By doing this the effect the screen, or the replacement, has on the corona can be estimated.

The setup will be modeled in a finite element program called Opera3d. Not all of the test setup will be modeled, only one part will be chosen. The part that will be chosen will have the highest concentration of corona in the setup or the lowest corona onset voltage. Corona onset voltage is the lowest voltage value were corona can first be detected. This leads to the following question:

Is it possible to construct a corona screen or replace a part of the setup, to reduce the amount of corona present?

1.2 Thesis outline

Chapter 1: Introduction to the report and the problem which is to be solved. The setup in the laboratory is explained.

Chapter 2: Initial testing of the available setup in the high voltage laboratory. Detailed description about ionization and corona followed by analysis of the electrical field. This chapter also includes two finite element models designed to enhance the understanding of the electrical field that is formed when an object is energized.

Chapter 3: Description of the different partial discharge that can occur in a high voltage system. Description of the Omicron MPD-600 measuring device being used along with partial discharge testing performed at the laboratory.

Chapter 4: A finite element model is constructed for the connecting sphere. How the model is constructed is described along with electrical field calculations with values from the model. The model is supposed to validate the corona onset voltage found during partial discharge measurements.

Chapter 5: The connecting sphere is improved in this chapter. A new sphere is designed and calculated. The sphere is designed in such a manner that it can replace the existing connecting sphere and have no corona at 200 kV. Partial discharge tests are also performed to validate the sphere.
Chapter 6 and 7: Conclusion to the report and discussion about future improvements.

Chapter 2

Problem analyse

The system is initially tested in the laboratory and the amount of corona present in the system is investigated. It is important to conduct this initial experiment to see how much corona is present in the available setup and where it is located. By analyzing the source of the corona, further investigation can be made in FEM analysis as well as streamer calculations in Matlab.

2.1 Problem description

The setup to be experimented on in the laboratory consists of two 100 kV transformers that are cascaded so they produce 200 kV combined. There are two things connected to the transformers and those items are an coupling capacitor rated at 300 kV and two series connected 100 pF capacitors. The series connected capacitors are used as a voltage divider for measuring AC voltage. A drawn figure of the setup is shown in 2.1. An actual photo of the setup can be seen in figure 1.1.

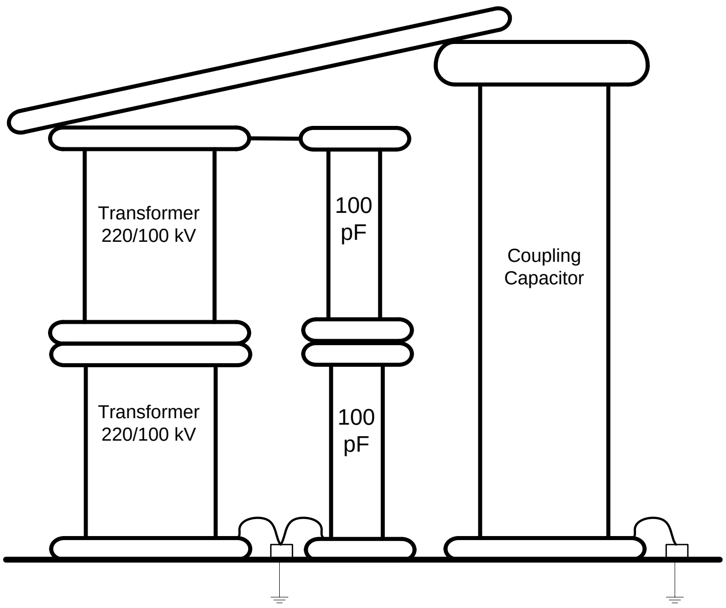


Figure 2.1: The setup used in the laboratory.

The coupling capacitor is connected to the transformers with a big metal rod, the rod needs to have a large enough curvature of radius on the end of the rod, so there should not be any corona on the end. A figure of the rod can be seen in 2.2.

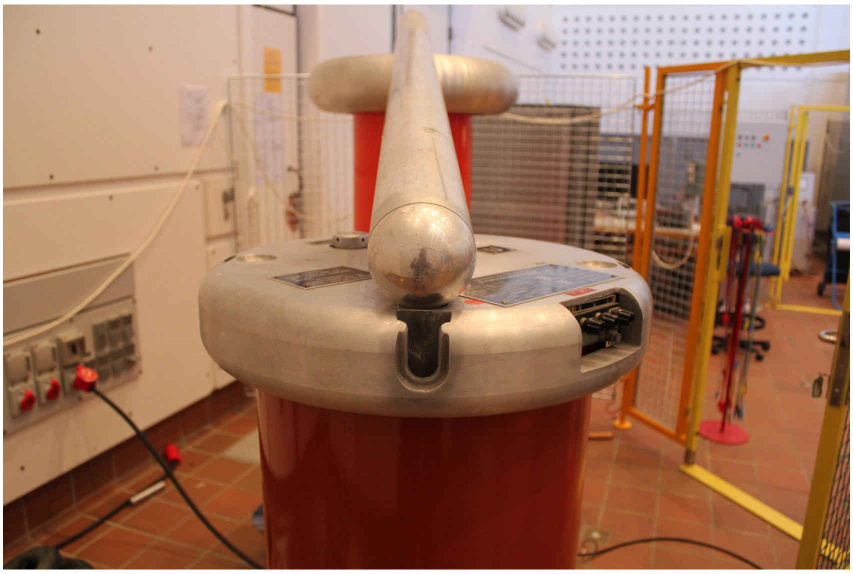


Figure 2.2: The metal rod that connects the transformer to the coupling capacitor.

The voltage divider is connected to the transformers with the standard connecting equipment available in the lab.

2.2 Preliminary test

After the preliminary test there were apparent corona on three locations in the setup. The first location was the end of the big rod that connects the coupling capacitor to the transformers shown in figure 2.2. On the end of the rod is a small crack and in that crack the field intensity becomes so large that the air around it breaks down resulting in a steady stream of corona called a streamer [25]. This was quickly solved by turning the rod so that the crack touches the surface of the transformer resulting in a lower electrical field at that location.

Corona is also present in the connection sphere from the transformer to the capacitive voltage divider. A figure of the connecting sphere is shown in 2.3.

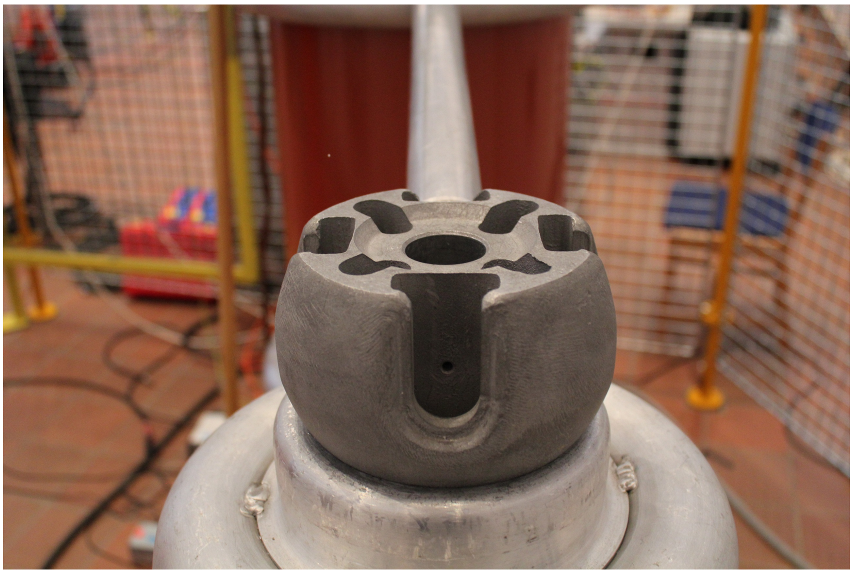


Figure 2.3: The connecting sphere.

There is also corona present at the top electrode of the transformer being used in the setup. A closer look of the top electrode can be seen in figure 2.4

Figure 2.4: The top electrode of the transformer.

Based on the preliminary test of the setup there were PD activity on three separate locations on the setup. One was solved quickly by turning the metal rod connecting the transformer to the coupling capacitor. The remaining two places, the connecting sphere and the top electrode of the transformer will be looked at more closely. It is also apparent that the corona onset voltage is lower for the connecting sphere than the top electrode of the transformer. Therefore the connecting sphere will be the main focus for improvement in the setup for the report.

The connecting sphere will be modeled in the Opera3d FEM program to see how the electrical field lines are distributed on the connecting sphere. The connecting sphere has some sharp edges that can be seen in figure 2.3. These edges do have a significantly lower radius of curvature than the sphere which result in a higher electrical field concentration.

When the main problem areas of the connecting sphere have been identified some sort of a hat or a shield will be designed to be placed on top of, or replace the connecting sphere to reduce the corona that is formed.

To begin with, the hat will be designed and modeled in the Opera3d program to see if it will have any effect on the field strength that is formed on the connecting sphere during testing. If the design shows improvement in the Opera3d program it will be built in the workshop at the university and tested on the connecting sphere. To determine if the screen that will be built in the laboratory has any effect in real life, a few tests can be done to determine its effectiveness. These test are visual observations and a partial discharge test.

Another option is to build a new connecting sphere that is more uniform in nature. This will be discussed later on in the report.

2.3 Ionization

What happens during a corona discharge is the ionization of air surrounding the conducting material. By taking a look at a normal atom there are neutrons and protons which form the core of the atom and there are electrons orbiting the core or the nucleus of the atom. This is shown in figure 2.5.

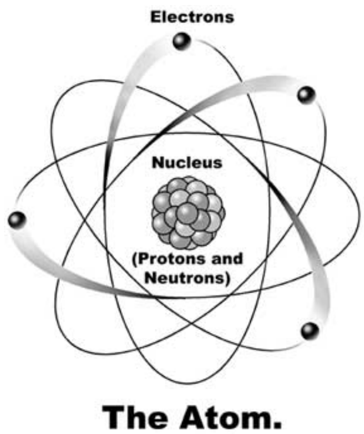


Figure 2.5: The structure of an atom [17].

The nucleus or the core of the atom has a positive charge and the electrons orbiting the core have a negative charge. The protons and electrons have the same electrical charge but of different polarity. The neutrons have no electrical charge but they do have the same mass as the protons. Under normal conditions the atom has as many protons, neutrons and electrons. When a material is excited the atoms in the molecule either give away one electron or add another electron. This process is called ionization, if the atom gives away an electron it becomes a positive ion and a negative ion if it adds another electron [14]. When an ion is exposed to an electrical field, either positive or negative. The ion will move to the object with the opposite polarity [23]. This is further shown in figure 2.6.

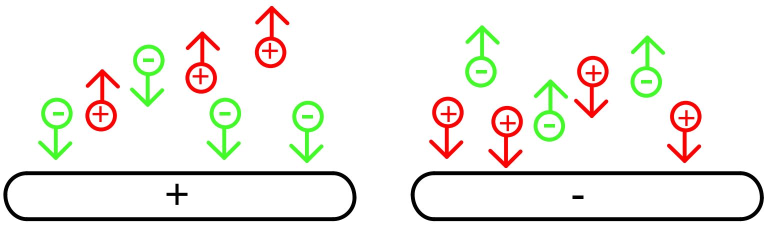


Figure 2.6: The movement of negative and positive ions subjected to different types of electrical fields.

Figure 2.6 shows ions of different polarity moving towards and away from to differently charged plates. The speed that the ions travel in, called drift velocity, is based on the electrical field strength they are subjected to and the mobility of the ion [23]. This is shown in equation 2.1.

$$v = E \cdot k \qquad [cm/s] \quad (2.1)$$

Where k is the mobility of the ion, where small ions have a mobility of 1-2 $\left[\frac{cm^2}{V \cdot s}\right]$ [23].

2.4 Electron avalanche

A corona at a surface of an electrical equipment is due to an electron avalanche which starts when the electrical field around the equipment surpasses a critical value. When an electrical equipment is energized and the resulting electrical field surpasses the critical value. Free negative ions will move towards the electrical equipment during the positive half cycle and away during the negative half cycle of the voltage wave. The speed of the ion is determined by equation 2.1. If the electrical field is sufficiently large then the ion can have enough speed to collide with another atom and knocking one of the atoms electron out of orbit. This process is called ionization [10]. After the collision both the old and the new ion have a relatively low velocity, but are again accelerated by the electrical field. A new collision will occur for both ions creating four more ions. This process is called electron avalanche.

After the electron avalanche there are a lot of positive ions left due to their slow velocity compared to the negative ions. Positive ions attract negative ions, when a negative and a positive ion are combined and create a neutral atom. The same energy is released as it took for the electron to break free during the electron avalanche. During this release of energy in the combination of a positive and a negative ion a visible light is emitted, also known as a corona glow [10].

Another way to explain this is by taking a look at a what happens during electrical breakdown in air. An energized rod, see figure 2.7 is placed above a plane (ground).

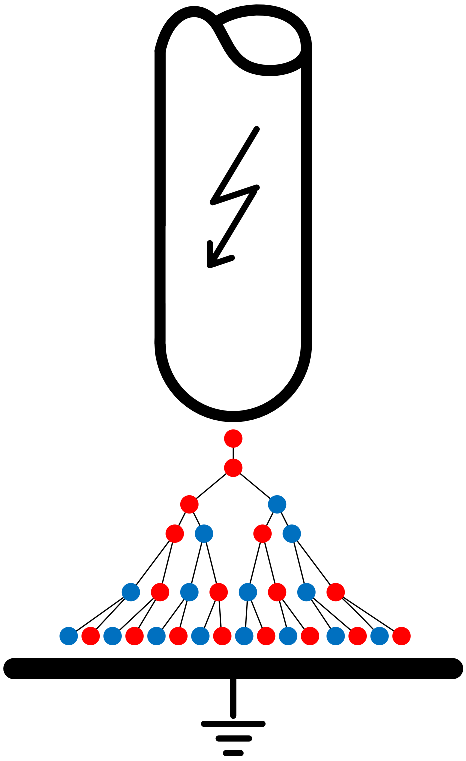


Figure 2.7: Rod to plain example with electron avalanche.

If the electrical field gets strong enough the air surrounding the metal rod will begin to break down. If the air brakes down it provides a path for the current to go from the rod to the plane. In other words the air starts to conduct current. This high electrical field forces the electrons to escape from the the atom core resulting in ionization. When the electron is moved further away from the core it can move more easily than before. The electrons ability to move more easily makes the air a better conductor therefore allowing the air to conduct current [21].

2.5 Electrical field distribution

To further understands what happens during energization of a material a closer look will be taken at two different examples. These two examples are modeled in Opera3d FEM program. The electrical field lines will be looked at and how they are distributed in each example.

By applying voltage to a rod above a plane a corona glow can occur.

The corona is affected by the radius of curvature the rod has, a smaller curve a higher concentration of corona will occur. By applying the same voltage to a rod with a larger curvature of radius the corona will be less or non existing.

In figure 2.8 the electrical field is shown including a theoretical graph of the electrical field strength and the critical voltage level (E_c) for corona inception.

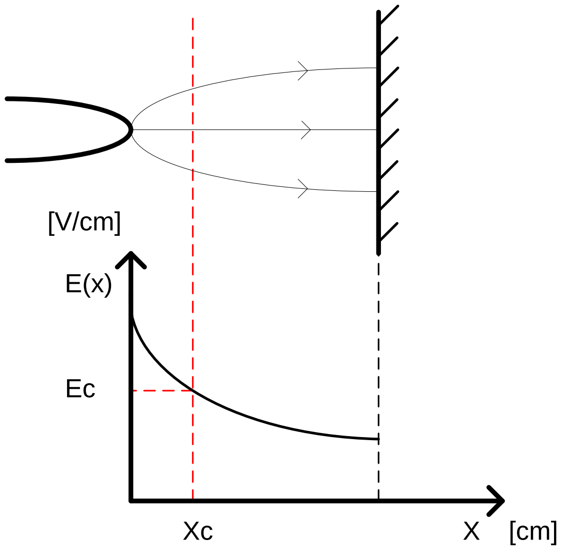


Figure 2.8: An example of the field distribution with an energized rod.

The area left of the red dotted line in figure 2.8, is where the electrical field E is higher than the corona onset voltage, E_c. Also visible in the figure are the electrical field lines from the rod to the plane. X_c is the distance where the electrical field E is equal to the corona onset voltage. The ionization region will increase by increasing the voltage applied to the rod and the corona will be come more visible. If the voltage is increased further it can result in a breakdown of the air between the rod and the plane.

2.6 Electrical field models

To make the previous theory more visible two examples have been modeled in the Opera3d program. Two examples are looked at in the program and they are coaxial cylinders and a rod to plane gap.

In figure 2.9, the rod to plane gap has been modeled in the Opera3d FEM program. In the figure the field lines are visible as purple arrows, and the color difference represent the electrical field concentration around the rod.

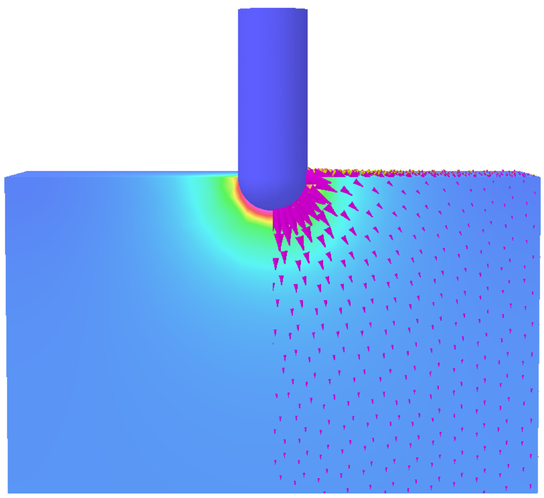


Figure 2.9: The Rod to plane example.

Note should be taken that the purple vectors that represent the field lines are formed perpendicular from the rod to the plane. The blue color in the figure represents the air between the rod and the grounded plain. The plain or the boundaries of the model are not shown in the figure.

Figure 2.10 is calculated with the Opera program and it represents the critical field line from the tip of the rod to the plane.

It is apparent from the graph that inside the rod there is no electrical field present, but at the tip of the rod the electrical field is at its greatest strength or E_{max}. By moving away from the rod the electrical field becomes smaller.

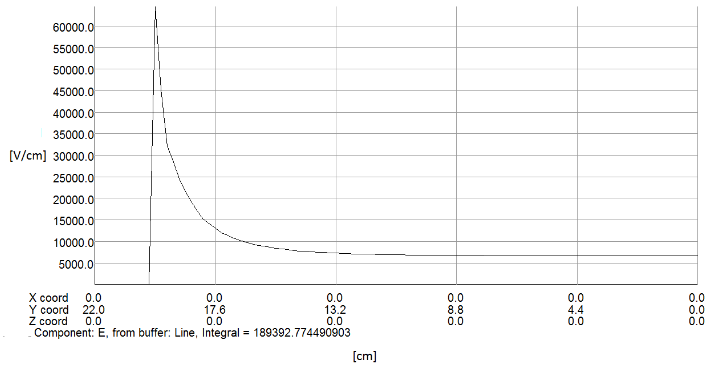


Figure 2.10: Electric field strength from the rod shown in figure 2.9.

The electrical field strength plotted in graph 2.10 starts at 22 cm on the y-direction, the tip of the rod is at 20 cm in the y-direction. For better illustration the coordinate system can be viewed in figure 2.11. The plain for the rod can also be seen. This shows that there is no electrical field inside the rod like previously stated. The electrical field does not start until the tip of the rod or at 20 cm in the y-direction. It should also be noted that the theoretical figure 2.8, has the same characteristics as the modeled graph in 2.10.

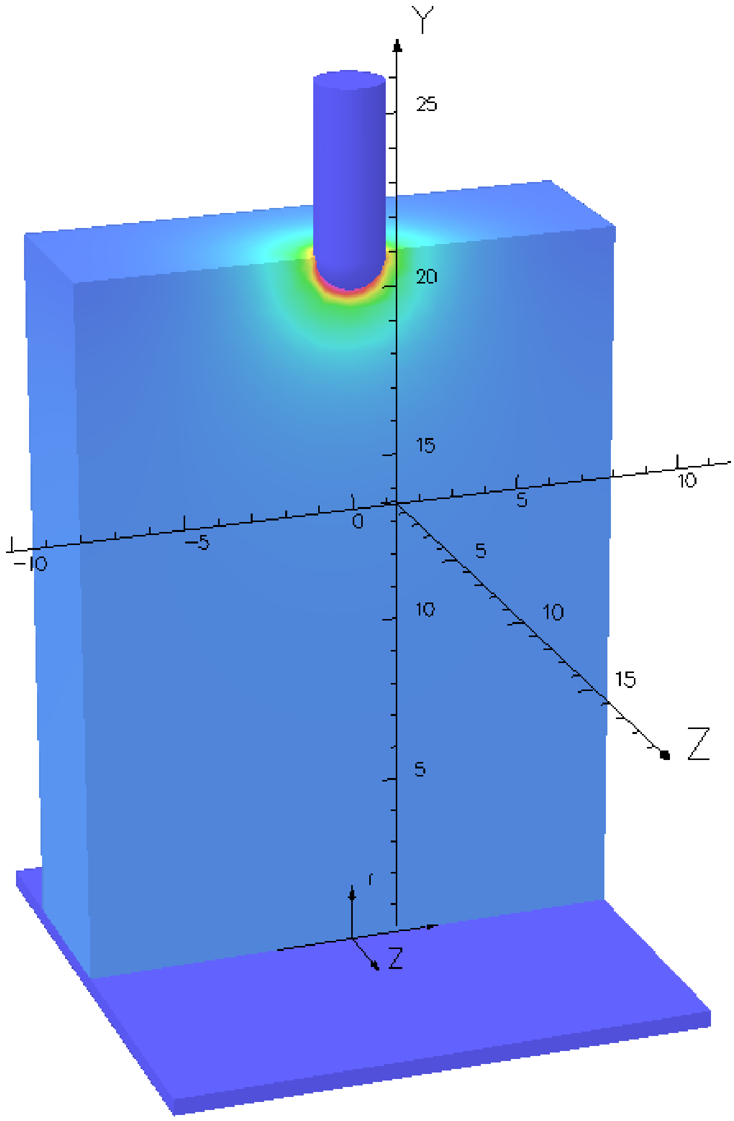


Figure 2.11: Illustration of the coordinate system used.

The field strength is further displayed in another example with a coaxial cylinders, which are also modeled in Opera3d FEM program. This example is intended to give a better understanding of the electrical field that can occur in a system. It is also intended to give a short validation of the model constructed for this coaxial cylinder example.

In figure 2.12 a small cylinder is placed inside a larger cylinder which is grounded. The inner cylinder is energized and the electric field strength coming from the inner cylinder and moving to the outer cylinder is examined.

Note should be taken that figure 2.12 is the cross section of the cylinders and therefore the end effect can be neglected.

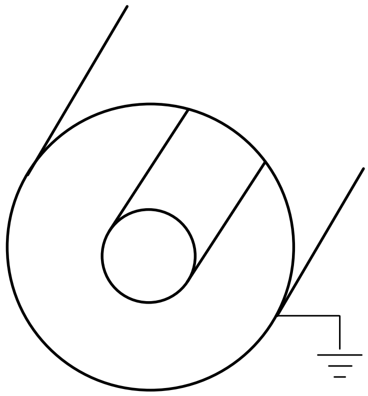


Figure 2.12: Coaxial cylinders example.

The example in the above figure will be modeled in the Opera program and the electrical field distribution will be examined. By having a standard example like the one in the figure, it is possible to calculate the electrical field at any given point withing the cylinder [9]. This will be done both on paper and in the model.

The equation to calculate the electrical field strength at a given point is presented in 2.2.

$$E(x) = \frac{V}{ln(r_2/r_1)} \frac{1}{x} \qquad [V/cm] \quad (2.2)$$

Where:

- V is the voltage applied.
- r_1 is the inner cylinder in cm.
- r_2 is the outer cylinder in cm.
- x is the distance in cm.

For this example an inner cylinder of 2 cm and an outer cylinder of 6 cm are chosen. The voltage for the inner cylinder is set to 20 kV.

By inserting the corresponding values into equations 2.2 the electrical field strength at a point 2 cm from the inner cylinder has been calculated. The values are presented in table 2.1. The same values are calculated with the Opera3d program and the values are slightly higher than from the calculation. This is due to the mesh size that the program uses. By increasing the mesh size, the calculated values for the program comes closer to the values calculated from equation 2.2. Due to the increasing calculation time it requires to have a significantly larger mesh in the program it is not practical to increase it any further.

Electrical field strength 2 cm from the inner cylinder	
Opera3d	4631 [V/cm]
Calculated	4551 [V/cm]

Table 2.1: Difference on the electrical field strength from the model and the calculated values.

This difference is further examined by calculating the field strength at 100 points for the previous example. From the surface of the inner cylinder to the outer cylinder, 2 cm to 6 cm respectively. The field strength is calculated with the Opera3d program as well in Matlab using equation 2.2. The results for these calculations are shown in graph 2.13

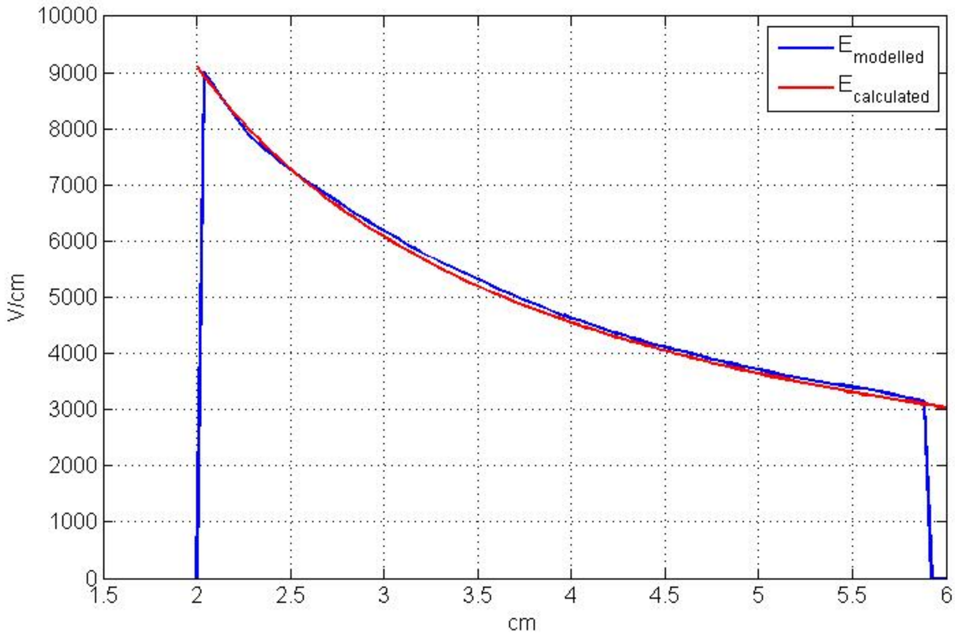


Figure 2.13: The curve for the field strength of the cylinder example.

In figure 2.13 the electrical field strength for the cylinder example is calculated with the Opera model and with Matlab using equation 2.2. The Matlab calculations are marked with a red line. The results are very similar, the Opera program gives a slightly higher results as previously stated. When moving closer to the outer cylinder the field strength drops suddenly for the model, this is due to the mesh size not having a point at exactly 6 cm from the inner cylinder. Based on the above calculation the model is considered accurate for this sort of calculations.

The model of the cylinder example is shown in figure 2.14.

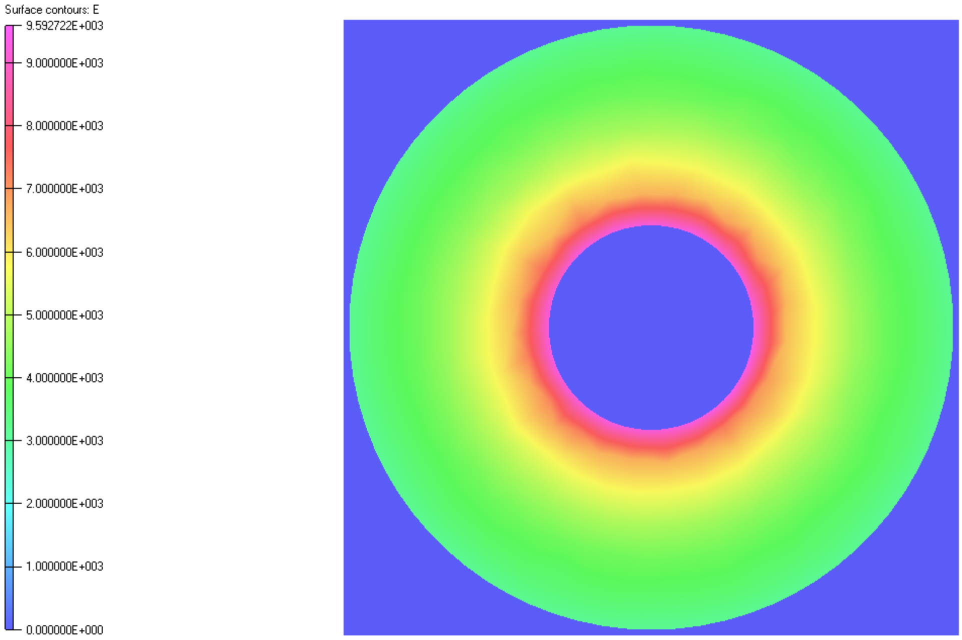


Figure 2.14: Electric field distribution for the cylinder example. Top view of the cylinders.

The electrical field is evenly distributed around the inner cylinder. Having the highest field strength on the surface of the cylinder and rapidly decreasing as it approaches the outer cylinder. Note should be taken that the blue box surrounding the outer cylinder is the boundaries for the model and they have the same characteristics as air.

By adding a small hemisphere to the inner cylinder in the previous example different results for the field strength are achieved. The hemisphere runs the entire length of the cylinder. This is shown in figure 2.15.

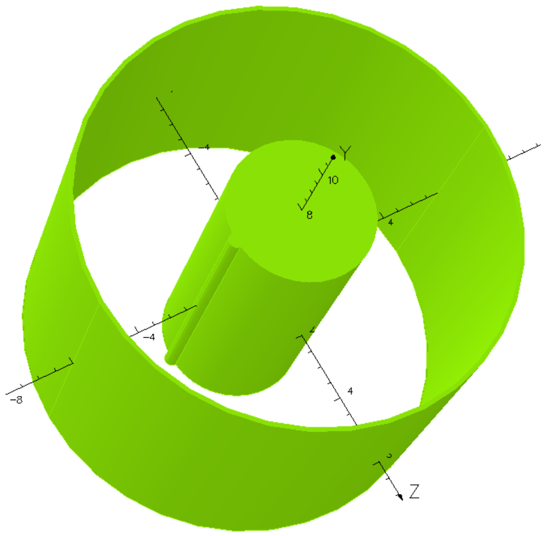


Figure 2.15: Figure of the added hemisphere on the inner cylinder.

The results of the new setup is visible in figure 2.16.

The small hemisphere that is on the edge of the inner cylinder has a small curvature of radius or 0.2

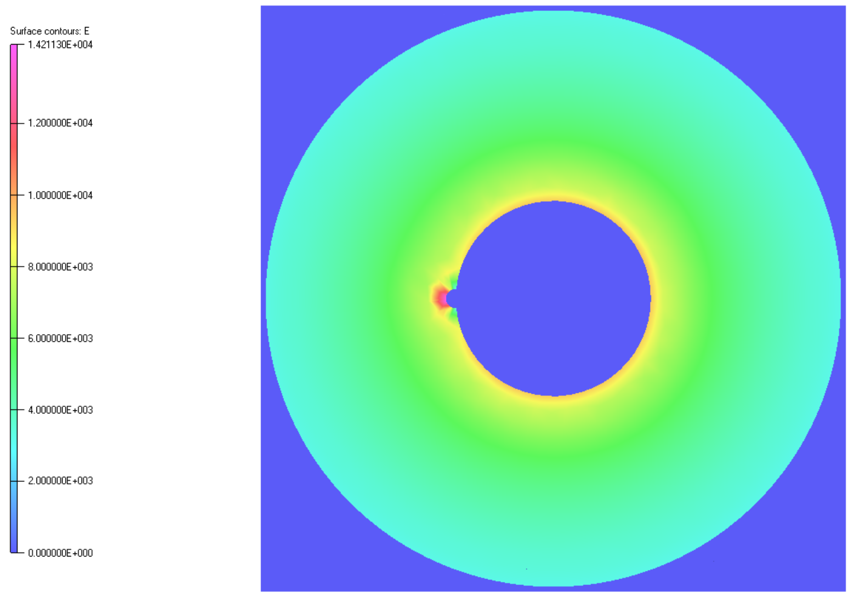


Figure 2.16: Electric field distribution for the cylinder with the added hemisphere.

cm. By applying the same voltage as before or 20 kV different results are achieved. The results for the simulation is visible in figure 2.16. The field vectors are more concentrated around the hemisphere, see figure 2.17, than on other parts of the cylinder. The field strength can also be observed to be higher around the hemisphere. This is due to a small curvature of radius of the hemisphere relative to the cylinder and the field becomes stronger with a smaller radius. Note should be taken that the scale in figure 2.14 and 2.16 is not the same resulting in different color concentration.

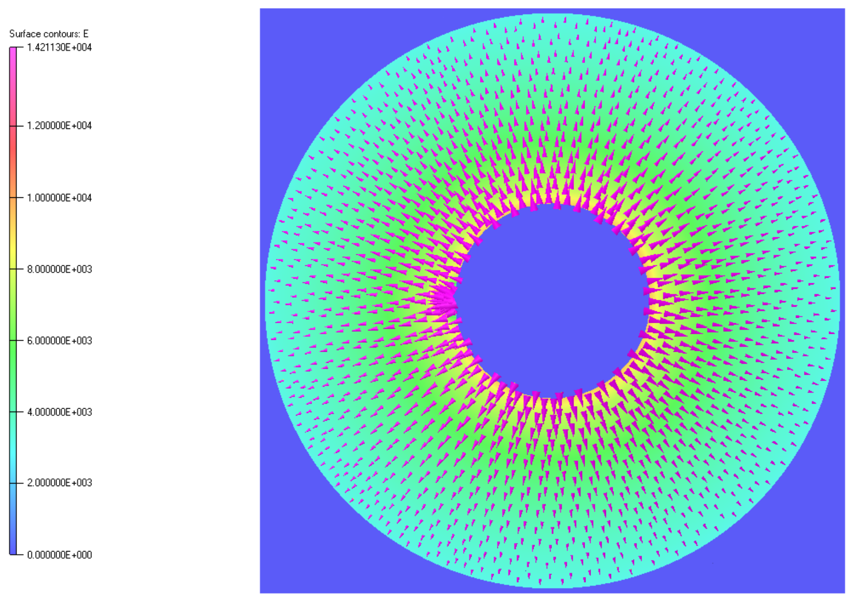


Figure 2.17: Electric field distribution for the inner cylinder with a small hemisphere.

The voltage level was the same for the previous two examples. The amount of electrical field, for the previous models, is dependent on two factors:

- The radius of curvature.
- The voltage level being applied.

By maintaining the same radius of curvature and increasing the voltages a stronger electrical field will be present. On the other hand maintaining the same voltages and decreasing the radius will have the same result.

2.7 Electrical breakdown example of coaxial cylinders

By taking a look at the coaxial cylinder example, figure shown in 2.12. The corona onset voltage can be calculated. These parameters are an inner cylinder of 2 cm, an outer cylinder of 6 cm and applied voltage of 20 kV. The equation used to calculate the corona onset voltage is given in [9] and shown in 2.3.

$$\frac{K/C}{\delta r} = \left(\frac{E_c}{\delta}\right)^2 - 2\left(\frac{E_c}{\delta}\right) E_0 ln \left[\frac{1}{E_0}\left(\frac{E_c}{\delta}\right)\right] - E_0^2 \qquad [-] \quad (2.3)$$

The different parameters in equation 2.3 will be given below.

- K/C is a constant defined to be 42 kV/cm [9].
- E_0 is the breakdown field strength defined to be 24,36 kV/cm [9].
- δ is the relative air density. This constant will be explained further below.
- E_c is the corona onset field strength and is found with equation 2.3.

δ in equation 2.3 is the relative air density, as the breakdown characteristics for air depend on the pressure and temperature of the air [9]. δ is determined with equation 2.4.

$$\delta = \frac{p}{760}\frac{293}{273+t} \qquad [-] \quad (2.4)$$

Where:

- p is the standard atmospheric condition in bar
- t is the temperature in Celsius.

For practical applications the temperature and pressure is set to standard atmospheric conditions of 20 degrees and 1.01 bar or 760 torr [24]. By inserting these numbers in equation 2.4 gives the relative air density to be one.

When the relative air density is set to one, it is then possible to simplify equation 2.3 to equation 2.5:

$$\frac{K/C}{r} = (E_c)^2 - 2(E_c) E_0 ln \left[\frac{E_c}{E_0}\right] - E_0^2 \qquad [-] \quad (2.5)$$

This equation can be used to find a value for E_c that fits with the calculated value from left of the equal sign in equation 2.5. The steps taken to solve equation 2.5:

1. By calculating $\frac{K/C}{r}$ with the previously given constants and setting r to 2 cm like previously stated a value of 21 is determined.
2. The number right of the equal sign should be the same as 21 and by isolating for E_c in equation 2.5. A value for E_c is determined to be 36,76 kV/cm.
   - The corona onset voltage is therefore 36,76 kV/cm.
3. By inserting 36,76 for E_c in equation 2.5 and leaving out $\frac{K/C}{r}$ on the left of the equal sign a value of 20,9708 is achieved.
   - 20,9708 $\approx$ 21 the condition for the equation is fulfilled.

The value found for E_c is consistent with a radius of 2 cm for the inner cylinder.

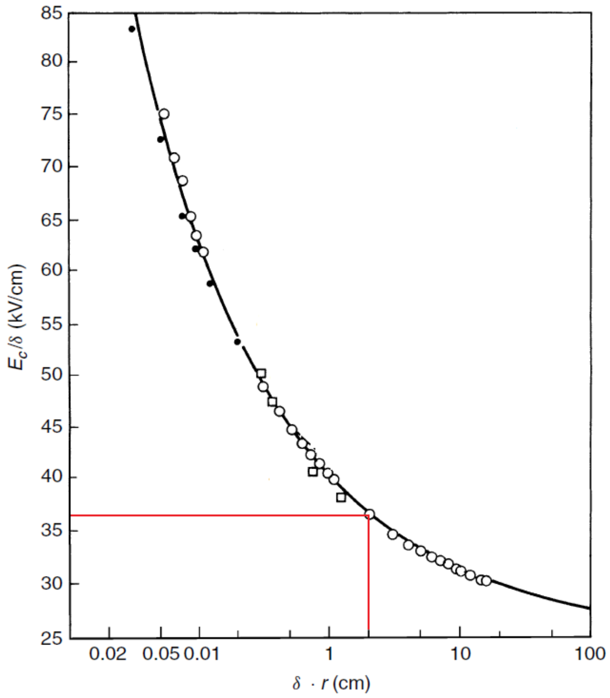


Figure 2.18: Variation of corona inception field strength (E_c/δ) against $\delta \cdot$ r for coaxial cylindrical geometry in air [9].

The points, solid, hollow and square in figure 2.18 are based on other measurements and calculations and should not be looked at further. The solid line in figure 2.18 is achieved with equation 2.3.

Now that the corona inception field strength E_c, for the given setup of coaxial cylinders of radius 2 and 6 cm, is known the voltage required to achieve this field strength can be calculated. This is done with equation 2.6 which is taken from [9].

$$E_{max} = \frac{V}{R_1 ln(R_2/R_1)} \quad [V/cm] \quad (2.6)$$

Equation 2.6 describes the maximum field strength or the field on the surface of the inner cylinder, based on a given voltage and radius for the inner and outer cylinder. The radius is known and the E_{max} is known from equation 2.5 as E_c.

By isolating for V in equation 2.6. A voltage of 80,77 kV are required to achieve a corona inception in the chosen example. By reducing the radius of the inner cylinder corona can be achieved with lower voltages than before. If the radius of the inner cylinder is reduced by 1 or set to 1 cm the required voltage would be 72,13 kV.

2.8 Electrical breakdown example of a rod to plane gap

Similar calculations can be made to the rod to plane example shown in figure 2.7.

For the given rod to plane example an inhomogeneous field is formed between the rod and the plane and it is possible to calculate if a breakdown or a corona will occur in the gap. This is done with Townsend's streamer criterion, shown in equation 2.7

$$\int_{0}^{x_c<d} \alpha dx = K \approx 18-20 \qquad [-] \quad (2.7)$$

The equation takes the integral from zero to X_c. A reference figure for X_c can be seen in 2.8. X_c indicates the length from the rod where corona inception can occur or where the electrical field strength E is equal to the inception field strength E_c, d is the length of the gap.

α is Townsend's first ionization coefficient. It describes the mean number of electron collision in the direction of the electrical field [8], or the success rate of an accelerated ion to collide with an atom and create more ions [5]. The electron increase in the field direction can be described by equation 2.8

$$dn = \alpha n dx \qquad [-] \quad (2.8)$$

Equation 2.8 describes the increase in electrons dn over a predetermined distance dx were n is the existing number of electrons in the field direction [3].

To be able to use equation 2.7 α is described by Schumann's empiric relation given in equation 2.9.

$$\frac{\alpha}{p} = C\left[\left(\frac{E(x)}{p}\right) - \left(\frac{E_c}{p}\right)\right]^2 \qquad [-] \quad (2.9)$$

Where:

- C is a constant, given by K/C = 45.16 kV/cm. C can then be isolated by choosing K as 18.
- E_c is also a constant of 24.36 kV/cm, which describes the breakdown field strength.
- E(x) in the equation is the electrical field between the rod and plane given in kV/cm.

Equation 2.9 can be simplified for air at standard atmospheric conditions then p is equal to 1 and the equation becomes easier to handle.

By inserting 2.9 into 2.7 yields 2.10

$$\int_{0}^{x_c<d} C\left[E(x)-E_c\right]^2 dx = K \approx 18-20 \qquad [-] \quad (2.10)$$

Steps taken to solve equation 2.10:

1. All units should be in kV.
2. Electrical field E_x is found for the rod to plane gap.
3. A value for X_c is found based on E_x then the integral can be calculated.

If the results for the integral are between 18-20 then there is corona in the rod to plane example. If the value is lower than 18-20 then there will be no corona in the gap. If this is the case for the rod to plane example then the voltage needs to be increased to increase the electrical field strength. Then the calculations can be made again with a new E_x and X_c. This will be shown in more detail later in the report.

Chapter 3

Partial discharge testing

Two types of partial discharge tests will be performed in the high voltage laboratory at Aalborg university to get an idea of how much, and where, corona is present in the setup. Two main tests will be performed to determine where and how much corona is in the test setup. They are partial discharge test and a sound test.

3.1 Partial discharge

According to [9] partial discharges include a wide group of discharge phenomena and they are defined as:

- Internal discharges occurring in voids or cavities within solid or liquid dielectrics.
- Surface discharges appearing at the boundary of different insulation materials.
- Continuous impact of discharges in solid dielectrics forming discharge channels [7].
- Corona discharges occurring in gaseous dielectrics in the presence of inhomogeneous fields.

The four previous points are taken directly from [9] and according to these different types of partial discharges only the last one is relevant for the project. The different types of PD are also shown in figure 3.1.

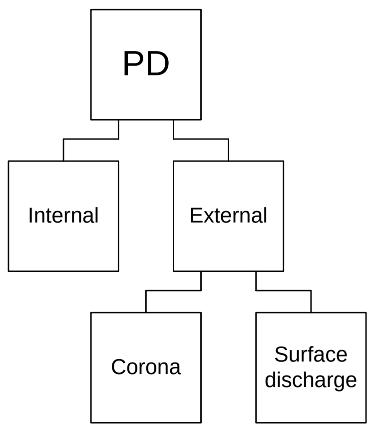


Figure 3.1: Different types of partial discharge.

By looking at figure 3.1 PD activity can be divided into two different categories and those are internal and external discharges. Internal discharges can occur in various electrical equipment such as paper insulation in transformers or in cable screening. There are more variations to internal discharges but they will not be presented here due to the relevance to the project. What defines the difference between internal and external PD is that internal discharges occur in cavities of an insulating material e.g insulating paper or transformer oil. Where on the other hand external discharges occur on the surface of the conducting material e.g. overhead lines.

External partial discharges are both corona in air and surface discharges. Surface discharges can occur between two different insulating materials e.g. on bushings on high voltage switchgear [26].

The first test that will be performed is by listening and determining where the corona is being formed. This is done by bringing the voltages slowly up and listening to when a hissing sound starts, that is formed when there is corona present. To do this an ultra sound detector is used.

The ultra sound detector has a parabolic screen that is attached to the front and that allows the detector to pinpoint where the origin of the sound is being formed. This is done by pointing the parabolic screen of the ultra sound detector at various points on the setup when energized and listening and trying to hear if there is a hissing noise at the location.

The second test that is performed is the partial discharge test. The basic principles of the partial discharge test circuit will be described in the next section.

3.1.1 Partial discharge testing

The standard circuit used for partial discharge tests is shown in figure 3.2

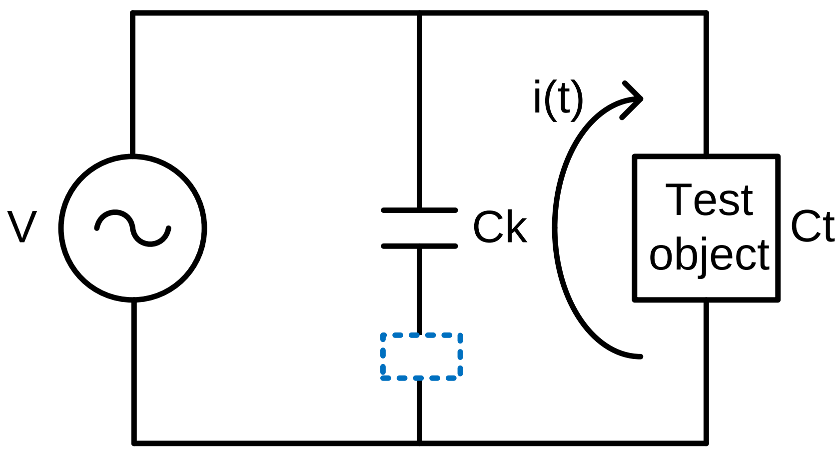


Figure 3.2: PD test circuit. The blue square represents the measuring equipment.

In figure 3.2 the test object is connected in parallel to a capacitor C_k. The C_k capacitor can also be called a coupling capacitor and according to [9] C_k should be as close to ideal as possible, and have no partial discharges. The test object shown in the figure can be any electrical component. The PD measuring instrument is usually connected on the low voltage side of the coupling capacitor, parallel with the test object. This is shown by the blue dotted square in figure 3.2.

The way that the circuit works is that a small current, i(t), is introduced between C_k and the test object.

When a partial discharge occurs in the test object the voltage over the test object drops momentarily. When the voltage drops the coupling capacitor tries to compensate for the voltage drop by acting as a voltage source for the test object during the partial discharge [9]. This results in a charging current i(t) between the coupling capacitor and the test object this current is the actual PD current pulse or the apparent charge that the partial discharge measuring device detects.

Internal discharges

For internal partial discharge figure 3.3 shows a stressed insulating material with a cavity.

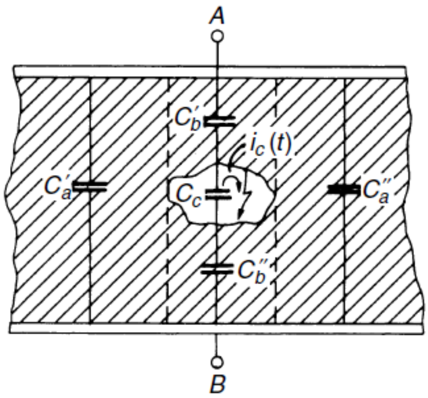


Figure 3.3: The different capacitance's in the test object [9].

The figure shows a test object to be tested for partial discharges and it has a cavity in the middle. C_a is the capacitance over the test object away from the cavity. C_c is the capacitance in the cavity and C_b are the capacitance on either side of the cavity. When the material is stressed a partial discharge current can occur in the cavity of the test object.

External discharge

For external discharges the equivalent test circuit is a little bit different than for the internal discharges. The circuit is shown in figure 3.4.

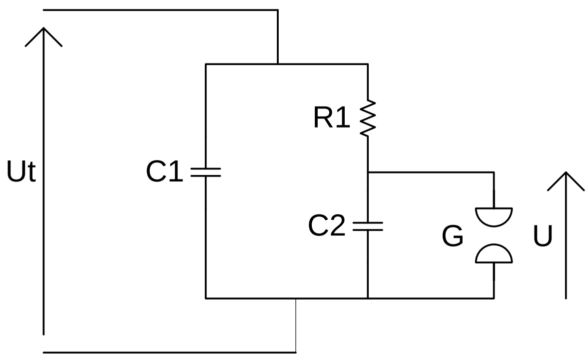


Figure 3.4: Equivalent test circuit for external PD [2].

The circuit in figure 3.4 can be used to describe the rod to plane example seen previously in the report. The C_1 capacitance is the normal capacitance of the rod to plane gap. R_1 represents active resistive losses caused by conductivity in the air. C_2 an extension capacitor that breaks down when the applied voltage reaches the breakdown voltage. G represents a spark gap which short circuits when C_2 breaks down [12].

During measurements of internal partial discharges corona disrupts the measurements and in the setup there should be no internal partial discharges in the equipment being used. All the charges the measuring equipment detects should therefore be corona.

During the actual testing in the laboratory the results of the partial discharge test will be documented and compared to the second set of test which will be performed after the construction of the corona screen.

The actual testing and calibration of the PD measuring unit will be described in section 3.2.

3.2 PD testing in the laboratory

In this section the actual PD testing that are performed in the laboratory will be described in detail, how the system is set up and the results will be presented.

The system is connected like shown in the figure below 3.5 .

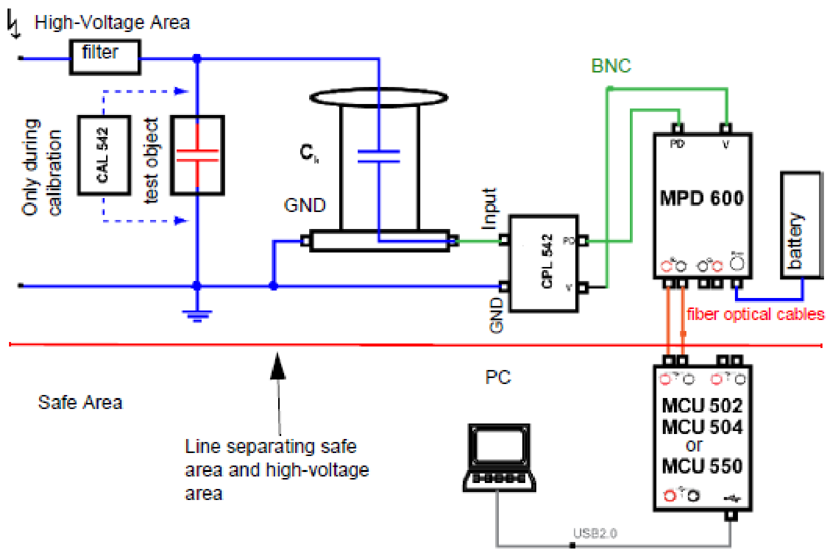


Figure 3.5: Connection schematic for the Omicron MPD-600 [15].

The configuration is a little different than in the standard setup shown in figure 3.5 because the device that is to be tested for PD is the top electrode of the transformer. Not some other device e.g. a cable or an auto-transformer. The voltage source is therefore the test object for this particular experiment.

The equipment that is used to conduct the PD measurements are the MPD 600 from Omicron. The measuring equipment consists of three different modules which will be listed below along with their function:

- MCU 502
- MPD 600

- Coupling quadripole

The MCU 502 is the control unit and is connected to the computer with an usb cable. This is the module that connects to the MPD 600 measuring unit. The MCU 502 is also the link between the high and low voltage side of the measurement circuit.

The coupling quadripole is a measuring impedance [11]. In figure 3.6 is a one line diagram of how the units are connected together, followed by figure 3.7 which is an actual photo of the three units that are used 3.7.

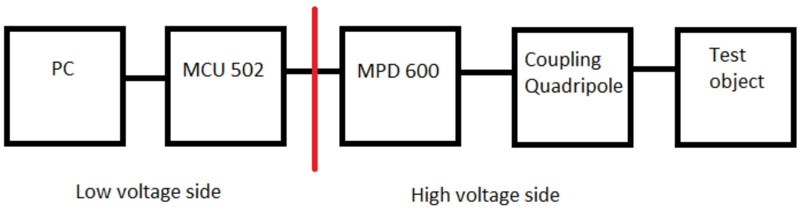


Figure 3.6: One line diagram of the units used for measuring PD.

Figure 3.7: The actual measuring units from omicron.

The MCU 502 is connected to the computer and it communicates with the measuring software from Omicron. A screenshot of the main measuring screen is shown below in figure 3.8.

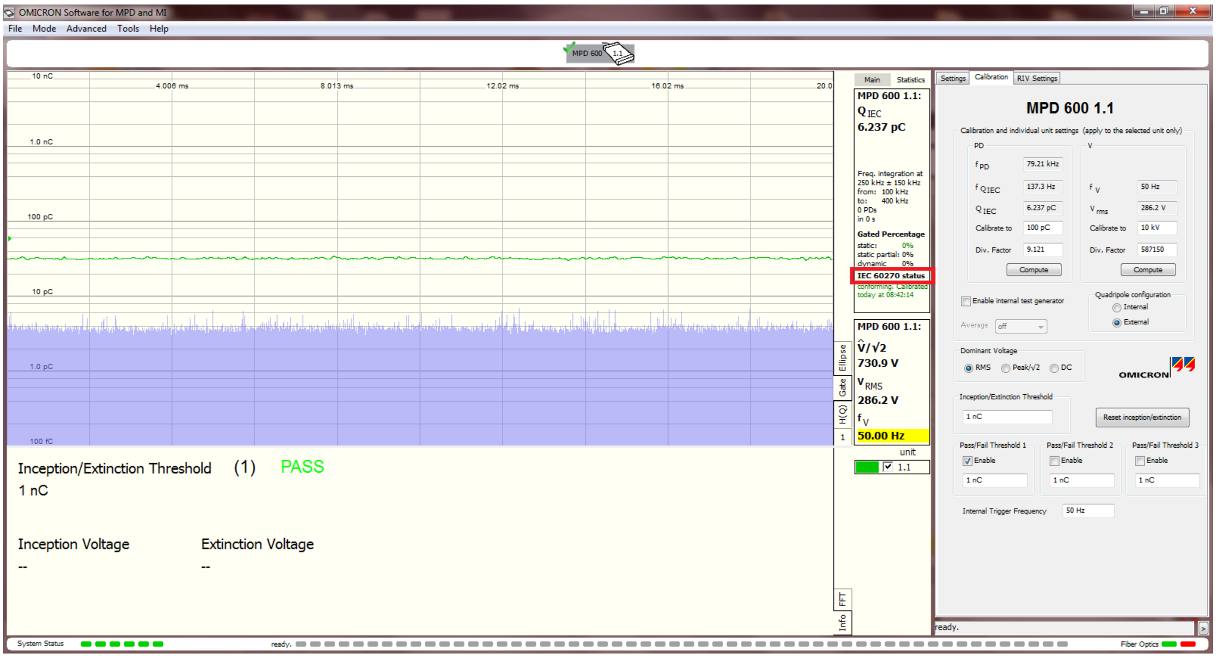


Figure 3.8: The measuring screen from the omicron software.

On the right side, of figure 3.8, is where the software is calibrated and setup for different uses. The left side shows the measurements. The red box on the right hand side of figure 3.8 shows that the unit is set up according to the IEC-60270 standard. The measurements are made in compliance with the standard [22].

3.3 Calibration of the Omicron device

Before the PD measurements can be performed the unit needs to be calibrated for the test setup that is to be measured. A new calibration needs to be performed every time the setup changes. To calibrate the software a PD calibrator is connected to the coupling capacitor and set to produce pulses of 100 pC. Note should be taken that the temporary earth needs to be removed from the setup before calibration takes place. The software then needs to be told that it is measuring 100 pC, a figure of the calibration results is presented in figure 3.9.

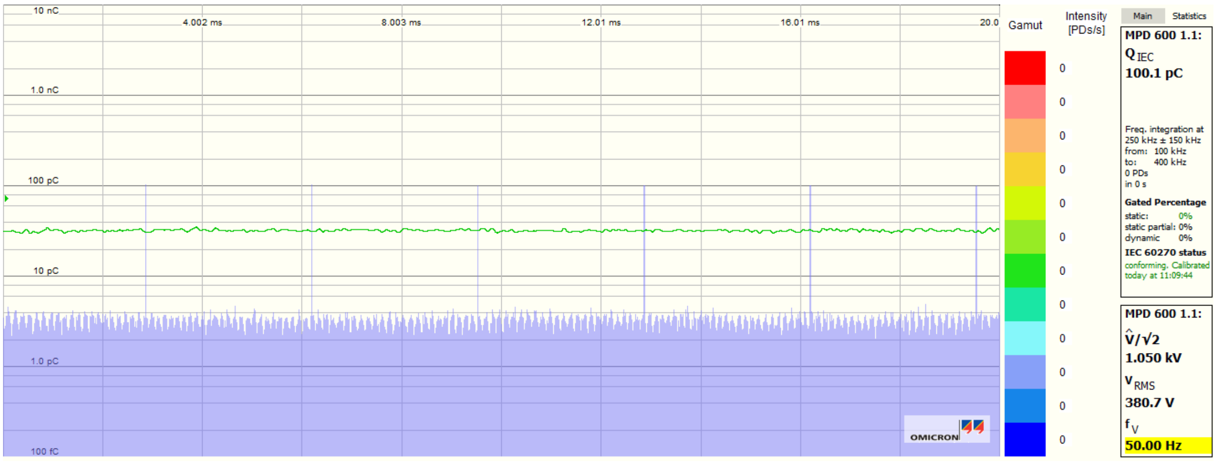


Figure 3.9: The calibration of the omicron software.

On the left side of figure 3.9 marked by Q_{IEC} is the apparent charge the unit measures and is at 100 pC like the calibration was set to. On the right side of the picture blue spikes can be seen going up to 100 pC. The other spikes that go up to around 5 pC are measured noises.

The voltage also needs to be calibrated. That is done in a similar manner as the pulse calibration. The circuit is energized to 10 kV and the software is told that it is measuring 10 kV similar to the pulse calibration of 100 pC. Note should be taken that the circuit is not energized during the pulse calibration, only for the voltage calibration.

3.4 PD testing

After the device has been calibrated the actual PD measuring can take place. The first thing that is to be measured is at what voltage level PD activity starts, what kind of PD activity is present and where on the setup. To determine where on the setup the PD activity takes place an ultrasound detector is used shown in figure 3.10.

Figure 3.10: The ultrasound detector.

The ultrasound detector shown in figure 3.10 is specially designed to detect PD activity. A set of headphones is attached to the device so the user can listen for PD activity before it can be heard with out the help of the ultrasound detector. The parabolic screen that is attached on the front of the device has an aim on it so the device can detect with pinpoint precision where the PD activity takes place.

To measure the exact voltage level the PD activity starts in the setup, the voltages are raised slowly until the Omicron device starts reading PD. The results of the first measurement can be seen in the following figure 3.11.

Figure 3.11: The PD starts at 114.2 kV. The red square marks the PD pulses.

Figure 3.11 is achieved by having the program measure and store all occurring PD activity for 30 seconds. This is done as soon as the PD spikes appear on the screen when increasing the voltages to find the onset voltage for PD.

The onset voltage for the setup is 114.2 kV and the type of PD activity that is occurring is negative corona in air [13] [4]. Corona is always apparent on the peak of the voltage curve in either the negative or positive polarity. Negative corona appears around 270° and positive corona appears around 90°. Based on figure 3.11 it is negative corona that appears in the setup.

The box in the top right corner in figure 3.11 shows the amount of PD measured in the 30 second interval and it also shows the apparent charge the unit is measuring. The box in the lower right hand corner shows the voltage and frequency of the applied voltage.

During the first test the location of the PD is also determined with the ultrasound detector. It is found that the PD activity occurs at the connecting sphere. The sphere is shown on the setup in figure 3.12.

Figure 3.12: The connecting sphere where the PD activity occurs.

Figure 3.13 shows a more precise location of where the PD activity occurs on the connecting sphere.

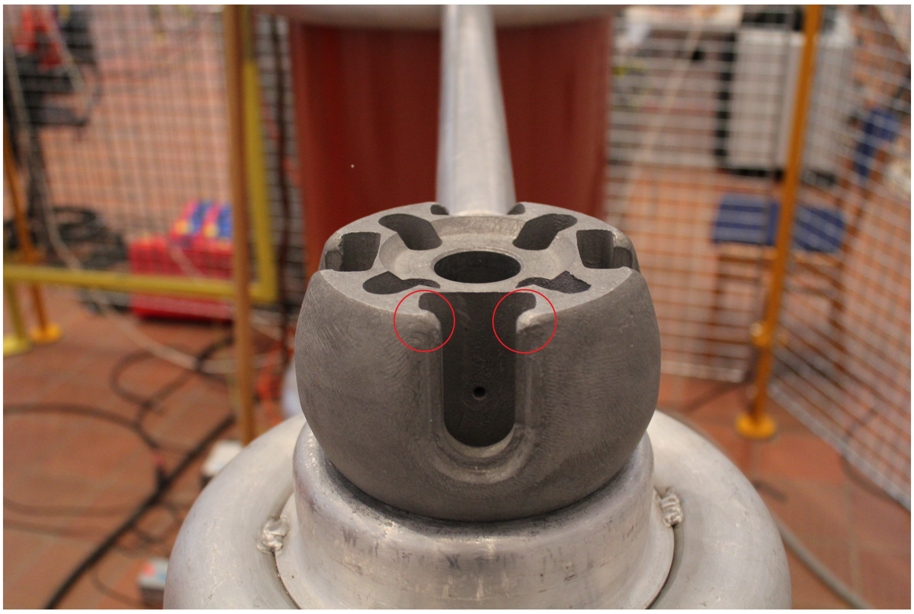


Figure 3.13: The red circles indicate where the PD occurs on the sphere.

The reason for the PD occurring where the red circles are marked in figure 3.13 is that the radius of curvature is smaller than on other places on the connecting sphere. Resulting in a higher concentration of the electrical field. It is interesting to raise the voltages above 114.2 kV to see if the PD activity increases in the setup. This is shown in the figure 3.14.

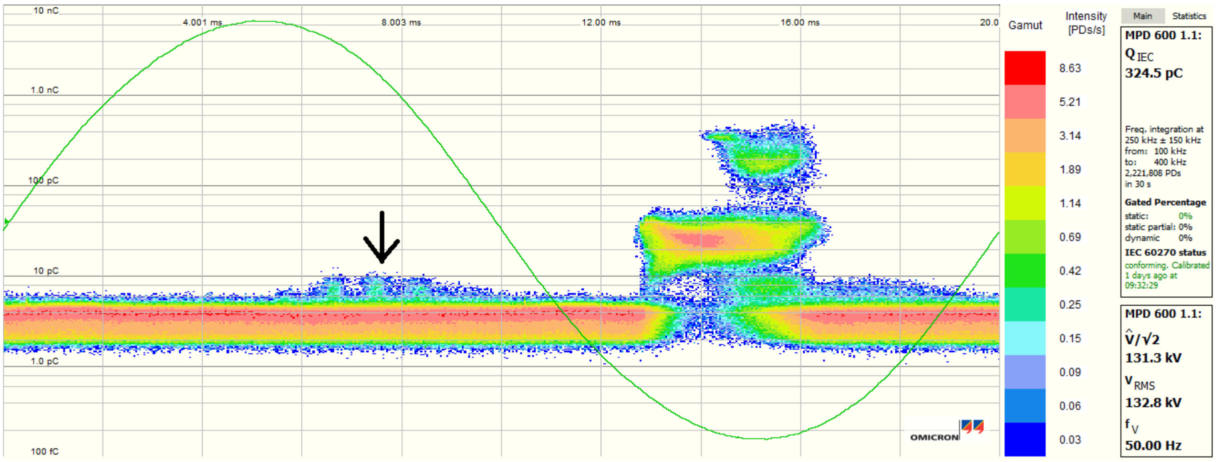


Figure 3.14: PD activity at 131.2 kV.

It is apparent from figure 3.14 that the PD activity increases with higher voltages. At 131.2 kV there is still negative corona. The arrow in figure 3.14 points to a little increase in the positive half plane of the voltage curve. This is added noise in the measurements from the negative corona. It is not positive corona due to the placement and size of the added PD pulses. Even though positive corona has a higher onset voltage than negative[13]. It is also interesting to note that at 131.2 kV corona effect can clearly be heard with out the help of the ultrasound detector.

This was the first test that was performed in the laboratory. It is apparent that corona appears first on the connecting sphere shown in figure 3.12. The objective of the rapport is to raise the voltages up to 200kV without having any PD activity in the setup. Therefore the connecting sphere will be looked at closer.

In order to reduce the corona activity on the connecting sphere a rubber tube is placed on top of the sphere, rubber is a semi conductor, and therefore could help in making the electrical field on the sphere more uniform. The rubber tube is shown in figure 3.15.

Figure 3.15: The rubber tube that is placed on the sphere.

The same test is performed again, the voltages are raised slowly until the Omicron measures PD activity. The results of the test with the rubber tube is shown in figure 3.16.

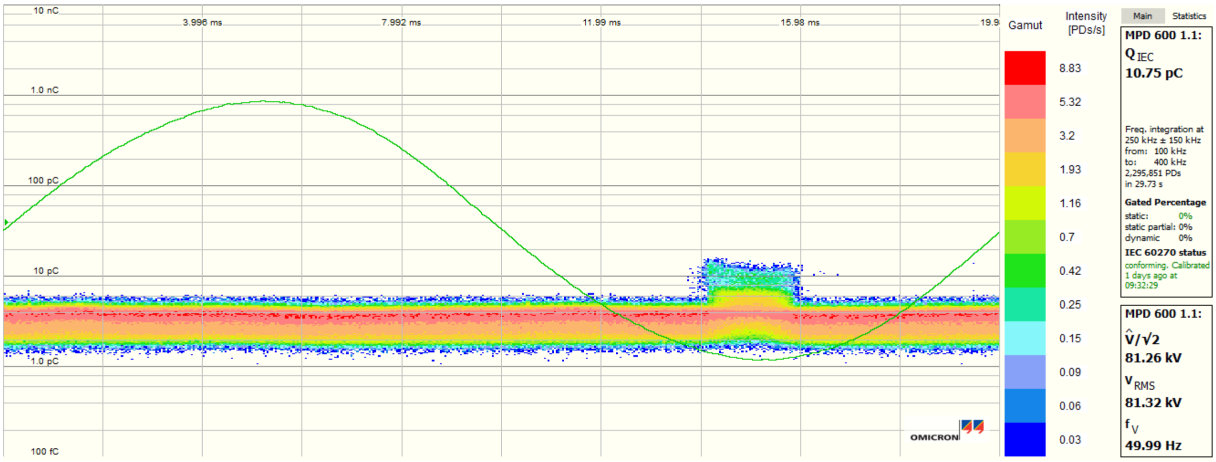


Figure 3.16: Results of the PD test with the rubber tube.

With the rubber tube connected the results are actually worse than without the rubber tube. Like shown in the test results in figure 3.16 PD activity starts at 81.26 kV and it was at 114.2 kV without the rubber tube. The PD activity that is present is again negative corona in air, the same as before. The reason for the rubber tube to give worse results than without the rubber tube can be because of the small air valve is made out of metal and has sharp edges. Due to the fact that the results are worse with the rubber tube than without it. No further testing will be conducted with the rubber tube.

By increasing the voltage above 114.2 kV it is unknown if there are other parts of the setup that have PD activity this will tested in the following test.

The transformer that is used is rated for 100 kV and there are two transformer used to achieve 200 kV therefore it is likely that the top electrode of the transformer will have some PD activity at higher voltages than 100 kV this will be tested next.

To test the transformer the capacitive voltage divider will be removed from the setup resulting in only the transformer and the coupling capacitor to be connected. The reason for this is that the PD detector from omicron can not distinguish where on the setup the PD is occurring and the ultrasound detector can not be used. This is because of the close proximity of the transformer to the measuring capacitors and the connecting sphere has an onset voltage of 114.2 kV and the corona can clearly be heard at 131.2 kV.

The results of the PD test with only the transformer and the coupling capacitor connected is shown in figure 3.17. Note should be taken that when the capacitive voltage divider has been removed the setup needs to be calibrated again. This will not be shown.

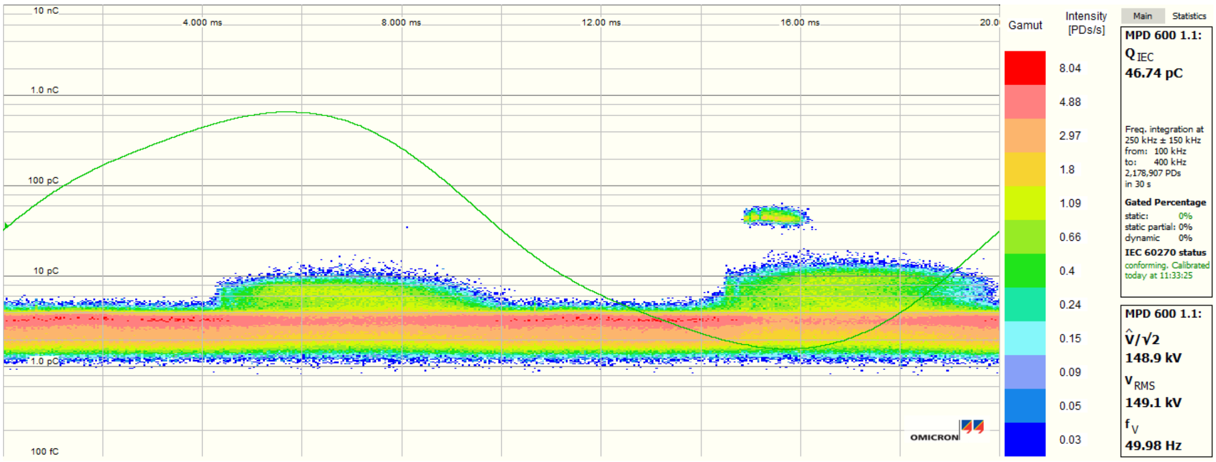


Figure 3.17: Results of the PD test with the measuring capacitor disconnected.

At 148.9 kV PD activity starts showing up on the omicron PD detector. The source of the PD is verified with the ultrasound meter and it is coming from the top electrode of the transformer. The type of PD activity that is on the transformer is also negative corona in air like in the previous two tests. It appears that positive corona is starting to form. This can be seen by the increase in PD pules on the positive half plane of the voltage curve. This could also be increased noise like in figure 3.14 In figure 3.18 the placement of the PD activity on the transformer is shown.

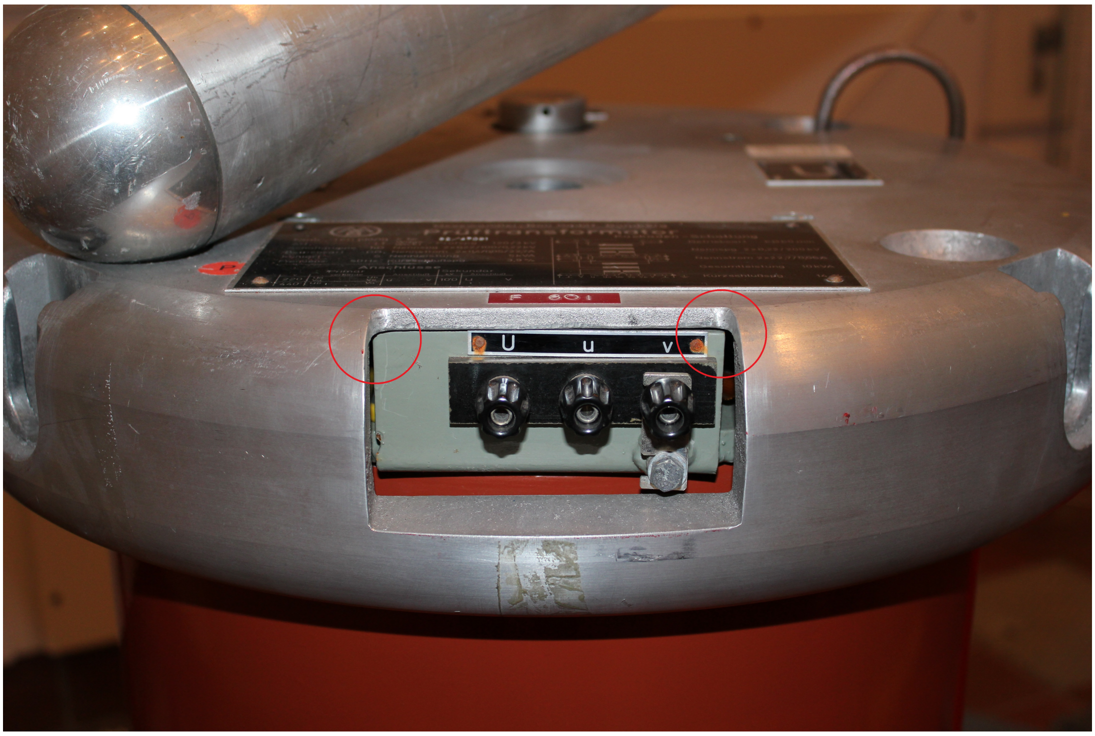


Figure 3.18: The placement of the PD activity on the transformer is marked with two red circles.

3.5 Visual tests

A series of visual tests are also performed to be better able to determine the source of the corona on the setup. Although the ultrasound detector gives an accurate placement it is interesting to be able to see the corona effect with the naked eye and that is not possible at the onset voltage level. To be able to see the corona effect the lights in the high voltage laboratory needs to be turned off and the windows need to be covered with drapes so that the room in completely dark. After the light have been turned off and the room is completely dark the setup is energized and the voltages are turned up to 180 kV. No measurements with the Omicron device are performed at this point.

At 180 kV the corona can clearly be heard by a loud noise coming from the setup. Purple streamers can clearly be seen coming from the connecting sphere and they are formed at the same place as shown by the red circles in figure 3.13. The corona that is on the transformer is not as apparent as on the connecting sphere this is because of the higher inception voltage for the transformer.

Figure 3.19 shows the connecting sphere in the dark where the streamers are clearly visible. Figure 3.20 shows corona effect on the transformer.

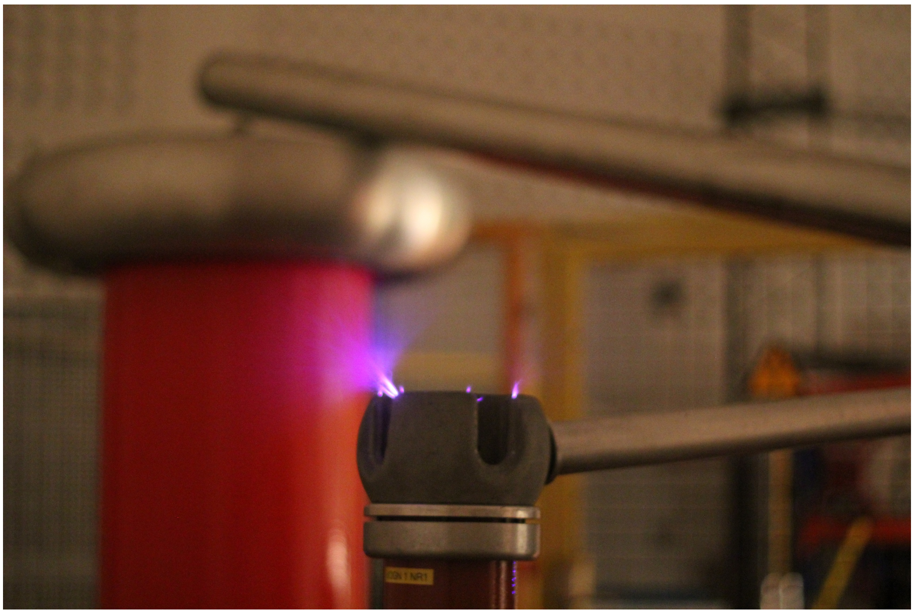


Figure 3.19: Visible streamer.

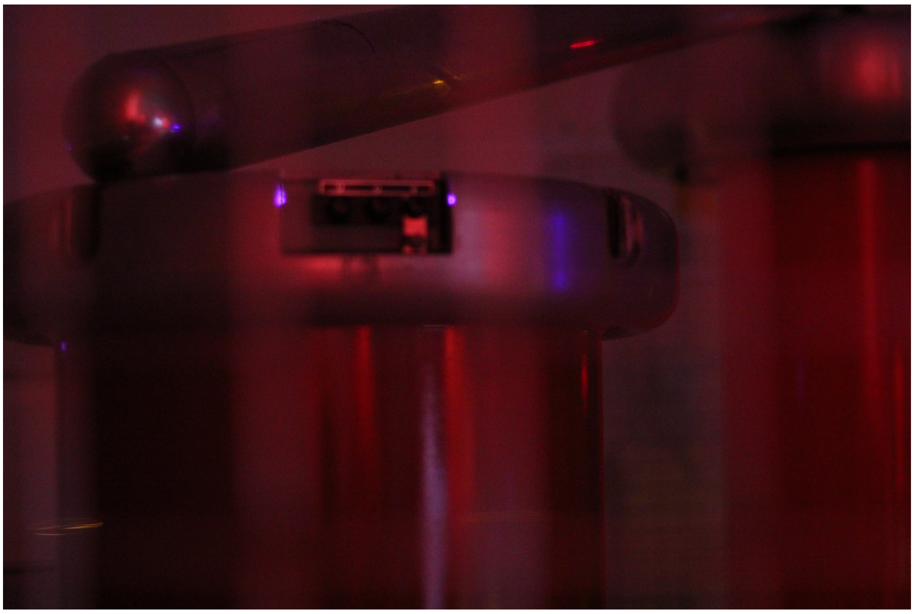


Figure 3.20: Visible corona on the transformer.

Based on the test above the main problem with the setup is the connecting sphere that has a corona onset voltage of 114.2 kV. The transformer has corona onset voltage of 148.9 kV. It is possible to fit a corona screen on the top electrode of the transformer but due to the connecting sphere having a lower onset voltage than the transformer the connection sphere will be looked at more closely. This will be discussed in chapter 4.

Chapter 4

Finite element model

In this chapter the connecting sphere will be modeled in the Opera3d FEM program. The purpose of this model is to verify the corona onset voltage and the PD measurements performed in the high voltage laboratory. The idea is to get an electrical field strength from the sphere at 114.2 kV and calculate using the streamer criterion if there is corona present in the model at that voltage level.

4.1 Model construction

Figure 4.1 shows the startup screen of the opera3d program.

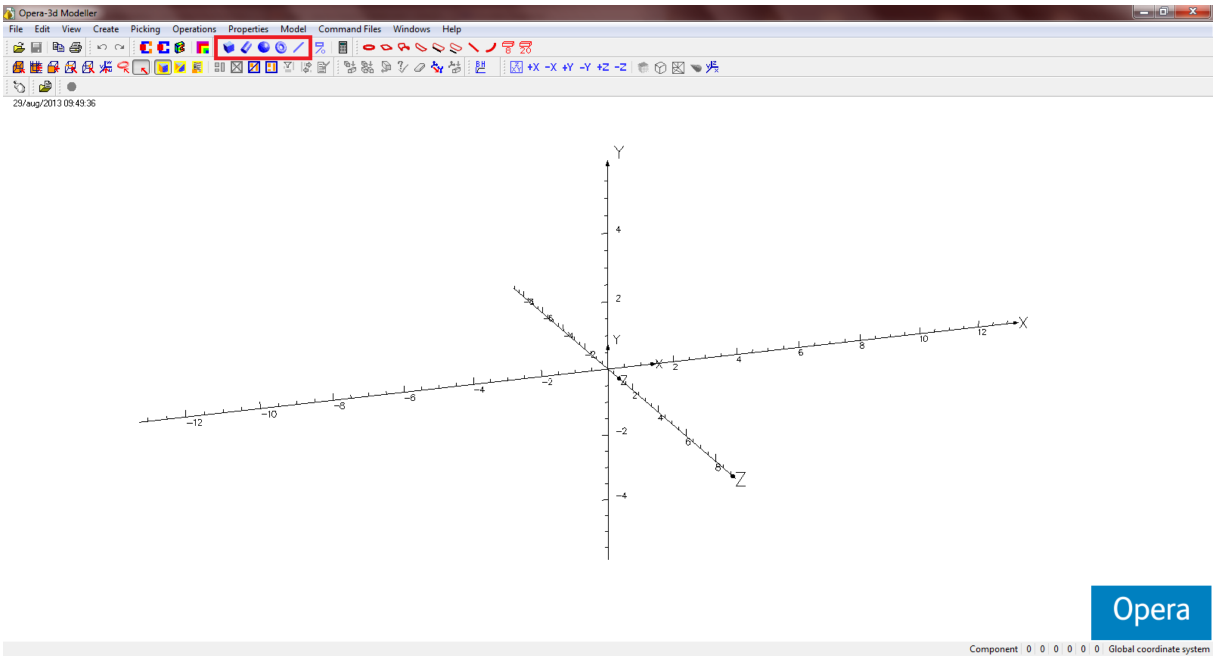


Figure 4.1: The startup screen of the Opera3d modeler.

The Opera3d model offers a variety of solvers to solve different finite element problems e.g. thermic and magnetic. The solver that is used is electrostatic and that solver is for solving electrical problems with a focus on electrical field strength.

The shapes that are possible to construct in the program are marked with the red square in figure 4.1. They are a block, cylinder, sphere and a torus. These basic shapes will be used to construct the connecting sphere. First a sphere of radius 7.5 is constructed and it is given the name Aluminum. This is shown in figure 4.2.

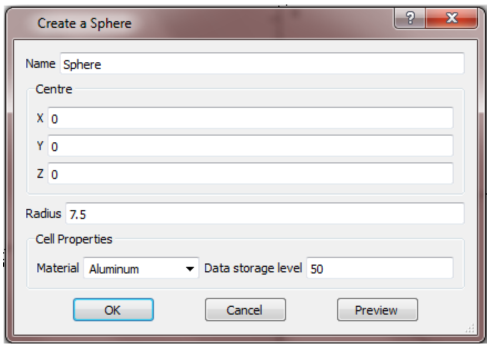


Figure 4.2: The starting sphere.

The next step is to build other blocks on top of the newly constructed sphere and subtracting them to create the desired shape. Due to the complexity of the connecting sphere only the basic steps will be shown. In figure 4.3 two blocks have been constructed on top of the sphere, this is to create the flat surface of the top and bottom of the connecting sphere.

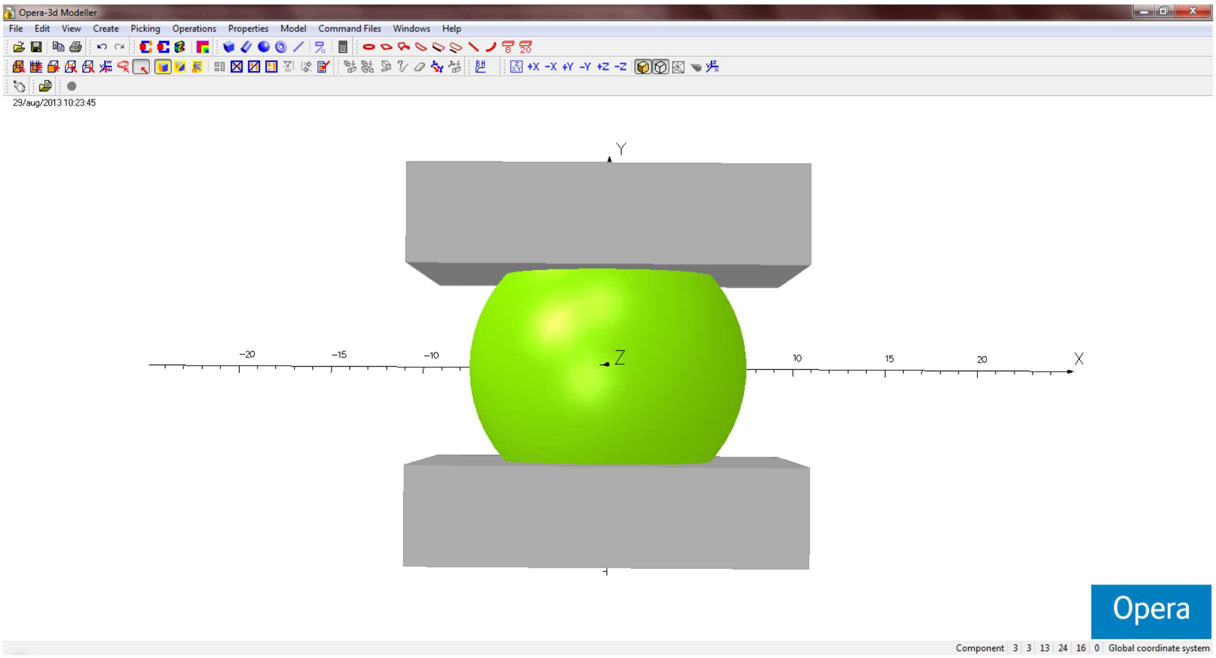


Figure 4.3: The two blocks used to cut the sphere.

The two blocks are then subtracted from the sphere and the results are shown in figure 4.4.

This process is continued buy building the default shapes available and subtracting them from the original sphere to create the final shape of the connecting sphere.

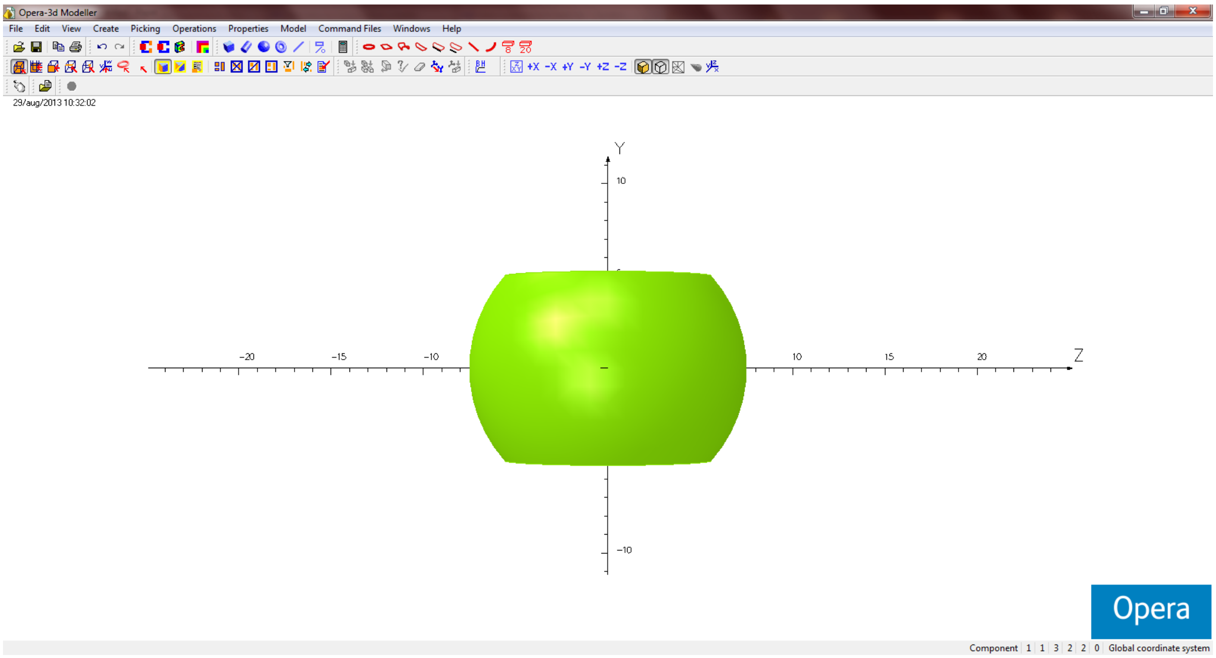


Figure 4.4: The sphere after it has been cut with the previous two blocks.

The final shape of the connecting sphere is shown in figure 4.5(a) alongside the actual connecting sphere 4.5(b).

(a) The connecting sphere modeled in Opera3d. (b) The actual connecting sphere.

Figure 4.5: The two connecting spheres.

The connecting sphere is made out of aluminum and it was shown earlier that the sphere that was constructed in the model was called aluminum.

The next step is to set the conductivity of the connecting sphere. This is done so that the model knows that the material is a conductor. It is unknown if the sphere is made out of pure aluminum or some sort of aluminum alloy. For the model it is assumed that the sphere is made out of pure aluminum with a conductivity of 3.538E+07 S/m [6]. This is done in the material properties tab.

The connecting sphere in the laboratory has a onset corona voltage of 114.2 kV RMS. The connecting sphere in the model is given the same voltage value. To give the connecting sphere a voltage value the outer surfaces of the connecting sphere are selected and given a name. This is done because the it is not possible to select the whole sphere and give it a voltage value. The surfaces or faces needs to be given voltage values. Below in figure 4.6 shows the surfaces of the model being selected.

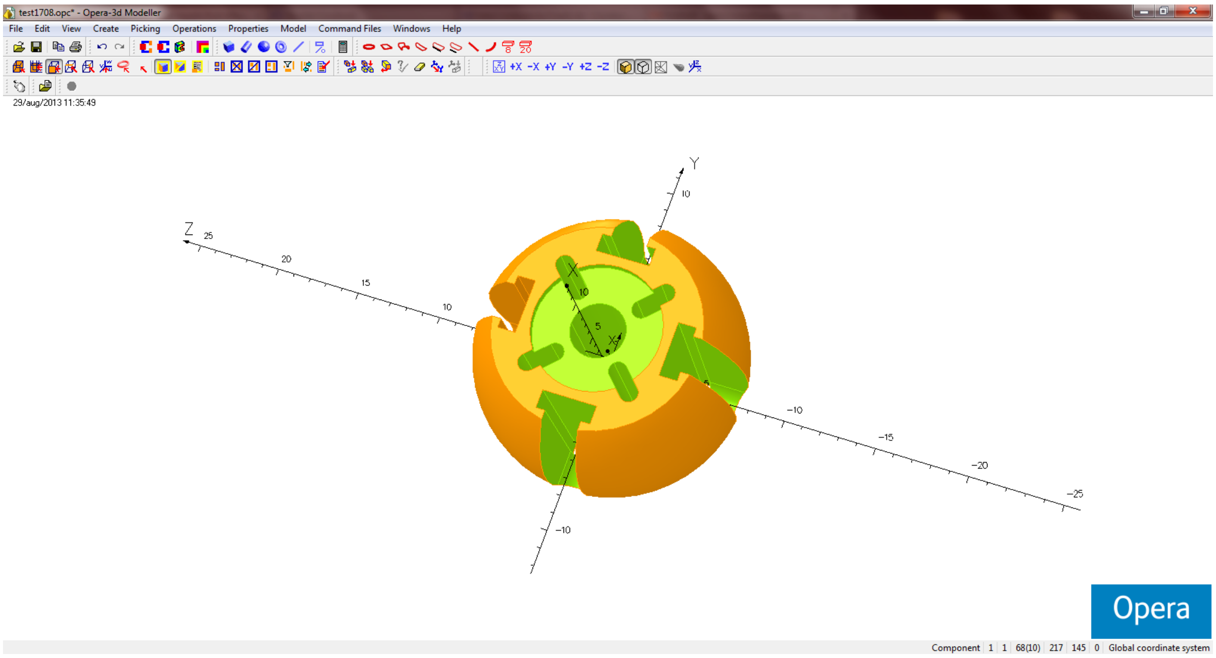


Figure 4.6: Faces of the model being selected.

The surfaces that have been selected are shown as yellow in figure 4.6 the ones that are still green are left out for illustrated purposes. All of the surfaces are selected and given a name (Voltage). All of the surfaces on the connecting sphere have to be selected in order to have the same voltage over the whole sphere. In the boundary conditions tab the boundaries of the model are given values this is shown in figure 4.7.

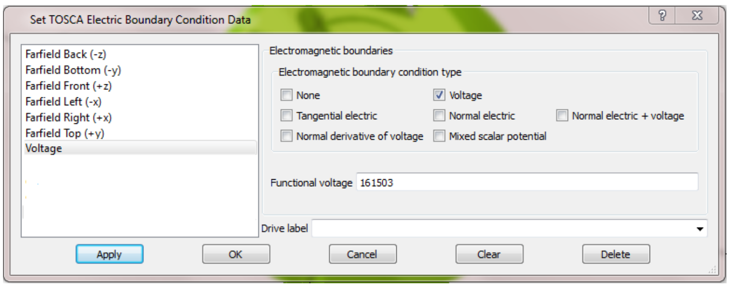


Figure 4.7: Defining the boundary conditions.

In figure 4.7 the voltage has been selected and given a voltage value of 161503 V witch is the peak value of 114.2 kV

4.2 Setting the models boundary conditions

To have the model as close to real life conditions in the laboratory as possible the model body is set to be at 150 cm away from the sphere which is approximately the distance to the walls of the laboratory at the university. Note should be taken that the top of the model body is also set to 150 cm but the ceiling of the laboratory is closer to 10 meters in height. It was therefore decided to have all the boundary conditions at the same length due to the electrical field which does not change much from 1,5 meter to e.g. 5,5 meters. For example an inner sphere of 9 cm and an outer sphere of 150 cm and 550 cm. If the inner sphere is energized at 200 kV and the outer sphere is changed from 150 cm to 550 cm the change in the maximum electrical field is only 4%.

The model body is divided up into four segments like shown in figure 4.8.

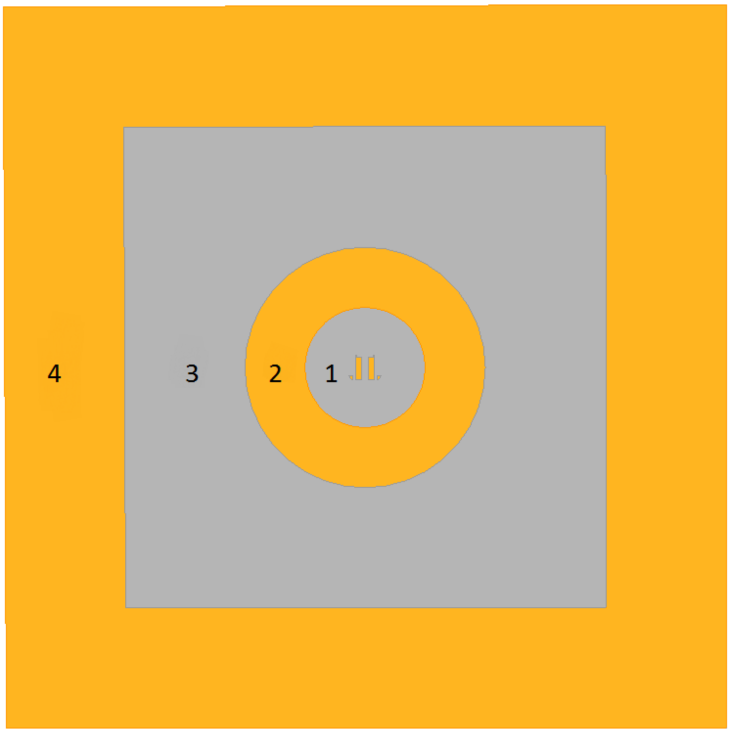


Figure 4.8: The four segments of the model body.

In figure 4.8 every other segment of the model body has been colored yellow to better distinguish the different segments. Every segment has also been given a number and their sizes will be described below.

- 1 is a sphere of radius 25 cm.
- 2 is a sphere of radius 50 cm.
- 3 is a box of length 100 cm.
- 4 is a box of length 150 cm.

This is better illustrated in figure 4.9.

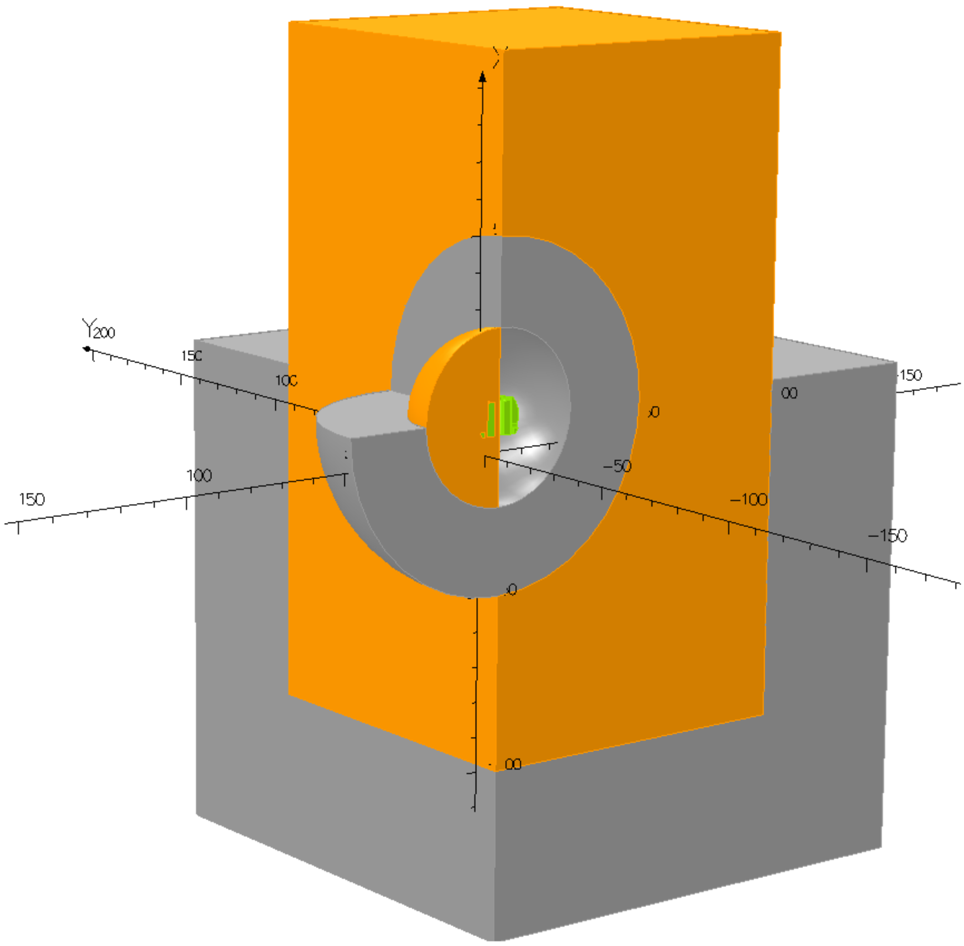


Figure 4.9: The four segments of the model body.

In figure 4.9 the model body has been cut up to better illustrate the different segments of the construction of the model body.

The reason for dividing the model body up to four segments is to be able to put different mesh sizes or mesh densities on the model body. The connecting sphere has the smallest mesh size and the sphere closest to the connecting sphere has a little increase in the mesh size. The mesh size gradually increases from segment to segment of the model body.

The idea behind having different mesh sizes is to get a better results from the model. By having a small mesh size the model should give better results, due to a smaller mesh size gives more calculating points for the electrical field from the connecting sphere. It is not possible to have all the model bodies with the same mesh size, this is due to the computing power available. It is easier for the computer to calculate a small segment closest to the connecting sphere with a small mesh size. By gradually increasing the mesh size the farther away from the connecting sphere requires less computing power. A figure of the mesh sizes can be seen in figure 4.10.

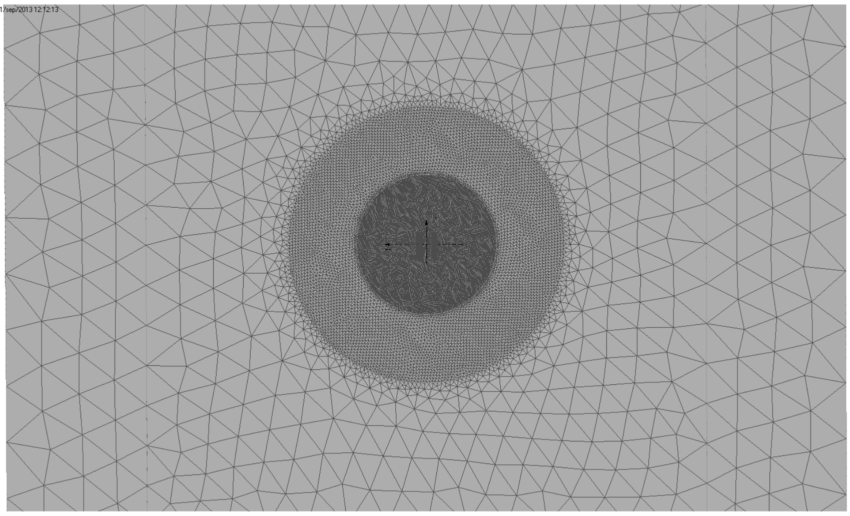


Figure 4.10: Different mesh sizes of the four segments of the model body. Only segments 1, 2 and 3 are visible.

It is clear from figure 4.10 how the mesh distribution is between the four segments of the model starts out small and gradually increases from segment to segment.

The figure below is a zoomed figure of the mesh size close the the connecting sphere and the model bodies have been cut like in figure 4.9.

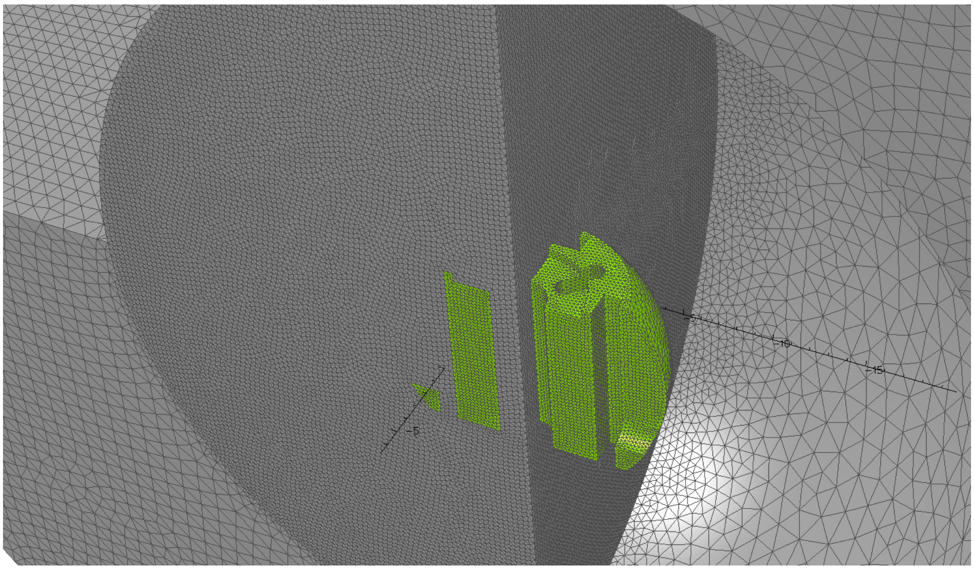


Figure 4.11: View of the mesh size close to the connecting sphere.

It should also be noted that the connecting sphere has been cut in half. This is done for easier computing time and less demand on the computer available. This should not have a big influence on the model results as the sphere is symmetrical, therefore it should give the same results by only having one half of the sphere in the model.

Two models will be constructed with different mesh sizes and the models will be compared. The first model will have the smallest mesh size the computer can calculate. The second model will have a slightly larges mesh sizes. The different mesh sizes will be presented below in table 4.1. The mesh sizes are given in cm [20].

Different mesh sizes for the models.		
	Mesh size [cm]	
	Model 1	Model 2
Connecting sphere	0,4	0,4
Sphere 1	0,6	1
Sphere 2	2	2
Box 1	15	15
Box 2	20	20

Table 4.1: Different mesh sizes for the two models

4.3 FEM model results

To compare the models a field line will be drawn from the connecting sphere in the direction that is assumed to contain the strongest electrical field. This is done based on figure 4.12

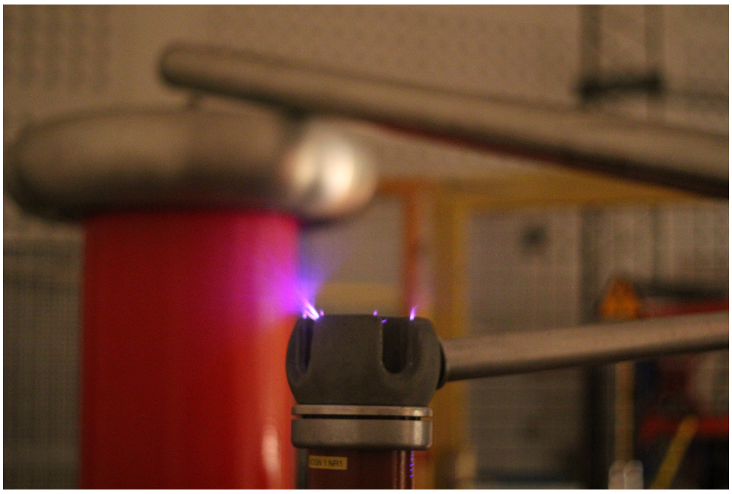


Figure 4.12: Corona on the connecting sphere in the laboratory.

By looking at figure 4.12 the corona or streamer can clearly be seen leaving the surface of the connecting sphere it appears to be leaving the sphere at a 45 degree angle. The same direction will be chosen in the model. The same direction will be chosen for both models and the electrical field strength will be compared.

The direction that is chosen is presented in table 4.2.

Field direction		
Coordinates [cm]	Start	End
X	4,5	25
Y	5	25
Z	1,05	1,05

Table 4.2: The chosen electrical field direction in cm.

The field line is shown in figure 4.13. The figure is taken from the Opera model and the black line represents the electrical field in the direction shown in table 4.2.

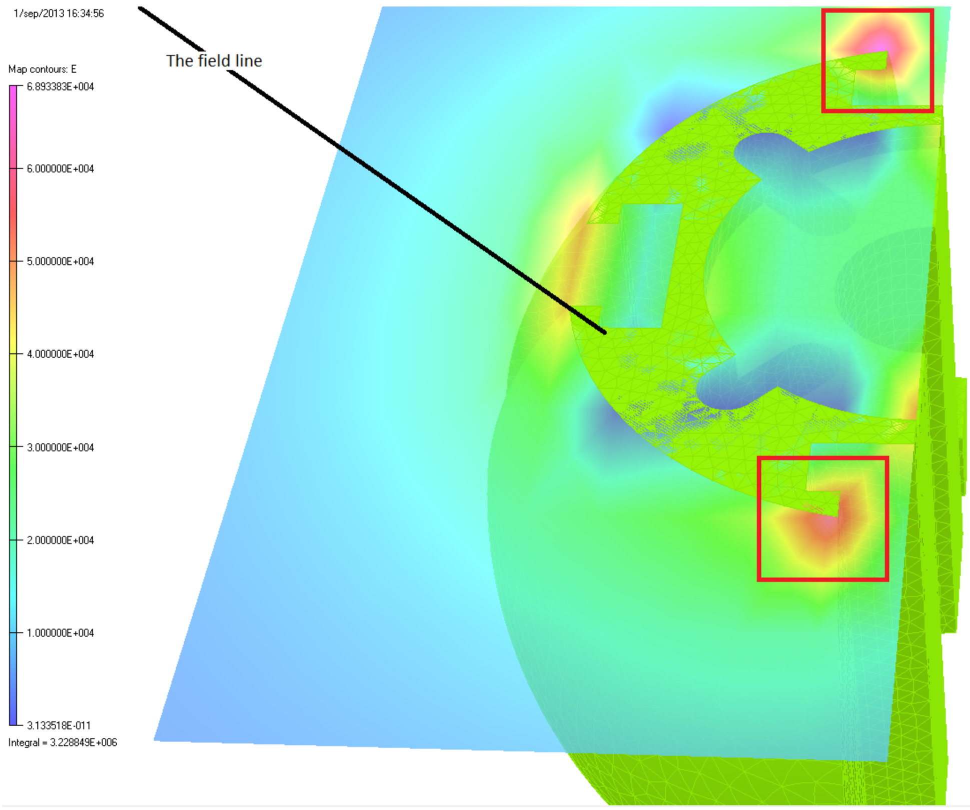


Figure 4.13: Electrical field line in the opera model.

The field concentration on the surface of the sphere can also be seen in the figure 4.13. It appears that the field concentration is stronger on the edge of the model where it is cut in half. This is disregarded due to the shape of the model. The model is cut in half and the area that is of interest is still whole, meaning it is not on the edge of the model where it was cut. This is further shown with a red box surrounding the area in question. Due to the close proximity of the edge of the model to where the field line is drawn it is unknown if the higher field concentration has an impact on the area where the line is drawn.

The field lines for both models are plotted using 10.000 points since the model is in 3D the actual length of the line is found with the help of Pythagoras theorem.

The actual length of the line is calculated in equation 4.1.

$$Linelength = \sqrt{(25-5,0002)^2 + (25-5,488)^2} = 27,94 \qquad [cm] \quad (4.1)$$

The z direction is not included in the calculation in equation 4.1 this is because the z direction does not change in the course of the line, the line is drawn directly along the z-axis, making this a 2D problem. Note should be taken that the start values for x and y directions are different in equation 4.1 than they are in table 4.2. This is due to the line starts inside the connecting sphere, this is done to be certain to get a data point exactly on the surface of the connecting sphere which results in the maximum field strength.

The line is plotted using 10.000 data points and the length of the line was found in equation 4.1 to be 27,94 cm. The length of the line is divided with the number of data points to find the displacement of the electrical field along the actual line.

The field lines are plotted, for both models in Matlab and the results are presented in figure 4.14.

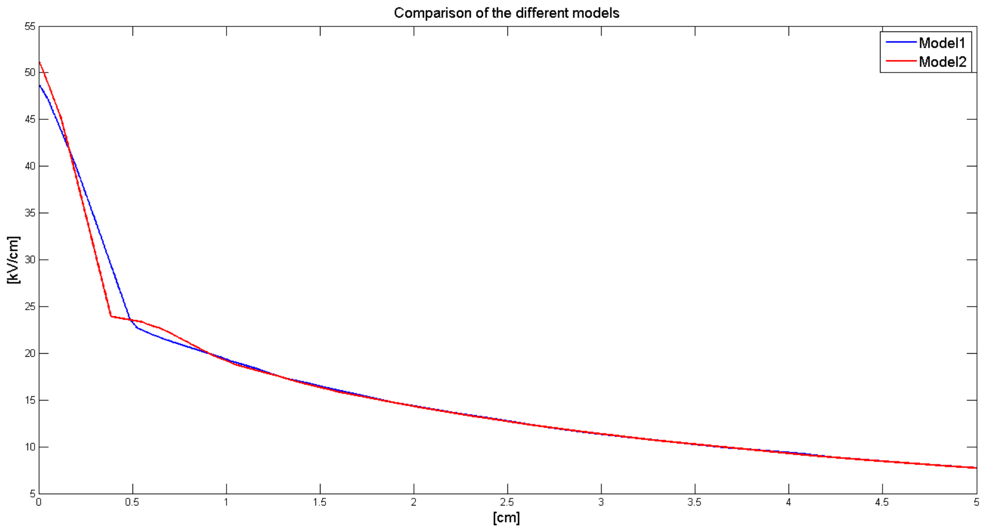


Figure 4.14: The electrical field lines from model 1 and 2.

It is apparent from figure 4.14 that the two models do not give the same results. According to [19] a finer mesh will give better results and this is one of the reasons a fine mesh was selected on the connecting sphere and the model body closest to the sphere. A closer look will be taken at both models results. The results will be calculated with the streamer criterion previously explained. The streamer criterion is shown in equation 4.2 for review.

$$\int_{0}^{x_c<d} \alpha dx \approx 18-20 = K \qquad [-] \quad (4.2)$$

The idea behind this is to see if there is corona according to the electrical field given by the two models. This is done by first finding a polynomial with the help of Matlab that describes the electrical field found in the model.

The polynomial is found with the help of Matlab by using a linear estimator. The linear estimator in Matlab tries to find a polynomial equation that gives the best fit according to the data points provided by the Opera model. The polynomial for the electrical field found in model 1 is shown below in figure 4.15, along with the curve found in the model and the curve for the polynomial.

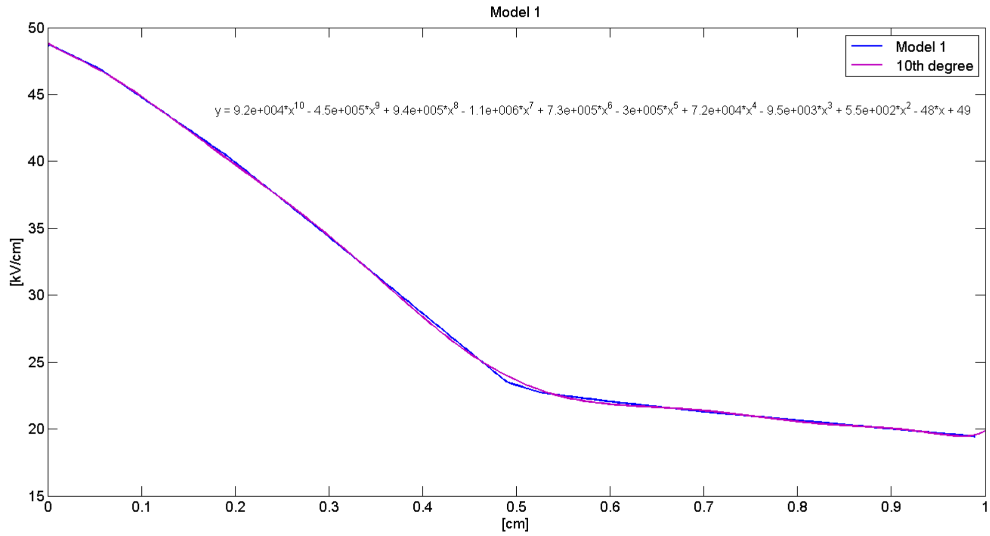


Figure 4.15: Polynomial for model 1.

Based on figure 4.15 the 10th level polynomial gives a good fit for the curve found in the opera model. Note should be taken that the x-axis only goes up to 1 in figure 4.15 but went up to 5 cm in figure 4.14. This is due to the polynomial does get a better fit by reducing the x-axis of the graph, this does not affect the results of the streamer calculation shown in equation 4.2. This is due to the critical distance X_c is still on the graph and in theory the field before the critical distance is the one that the calculation are based on. The polynomial for model 2 is found with the same method as model 1 but the results of the polynomial for model 2 will not be shown but the results for both models will be presented in table 4.3.

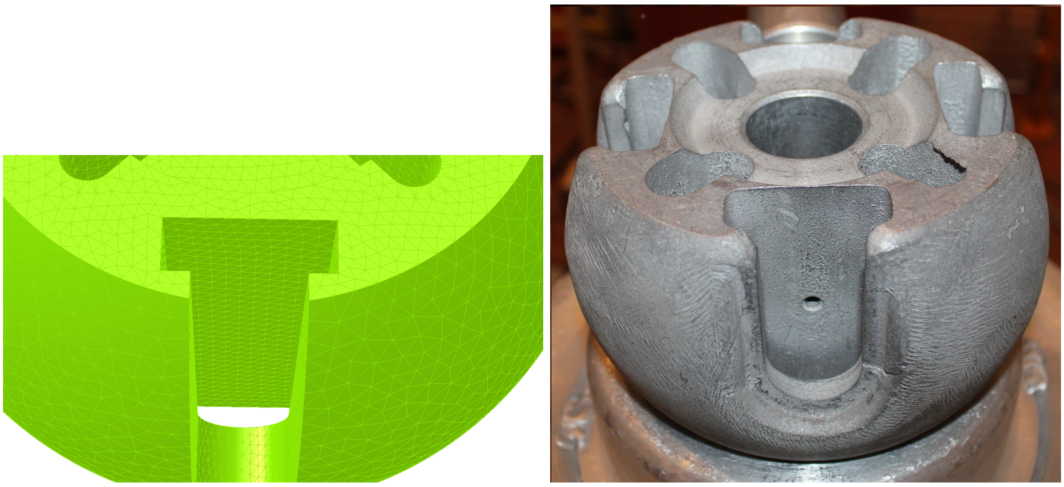
Streamer results for model 1 and model 2		
	Model 1	Model 2
X_c [cm]	0,48	0,39
K	42,31	42,42

Table 4.3: Streamer criterion results for model 1 and 2

It is apparent from table 4.3 that the K constant for both models goes over 18-20 resulting in corona or a streamer. The K value for both models is a little higher than expected, because the voltages in the model is the same as the onset corona voltage in the lab. Therefore it was expected that the K value would be little over 20.

The reason for this can be because of the mesh sizes being to large which results in inaccurate results or a higher field strength. Based on table 4.3 The K constant is a little lower for model 1 than model 2. Also by taking another look at figure 4.14 it is apparent that the maximum electrical field for model 2 is higher than for model 1. The maximum electrical field has a big impact on the results from equation 4.2.

Another possibility is the construction of the connecting sphere in the opera model. By taking a look at a zoomed in figure of the sphere in the opera model, shown in figure 4.16(a) and a figure of the actual connection sphere shown in figure 4.16(b).



(a) The connecting sphere modeled in Opera3d. (b) The actual connecting sphere.

Figure 4.16: A closer look of the modeled connecting sphere.

By comparing figures 4.16(a) and 4.16(b) there is a noticeable difference in the smoothness on the edges where the corona appears. The actual connecting sphere is smoother than the sphere constructed in the model. This additional roughness of the sphere in the model can have a significant results on the outcome of equation 4.2.

A different field line is drawn from model 1. This field line will be shown in figure 4.17. The idea behind this field line is that in the laboratory no corona was present at this location in the connecting sphere and it will be interesting to see what the results of the streamer criterion will be from this field line. The expected value should be below 18-20. This is done to validate the model and see if the K value will be lower than for the previous field line.

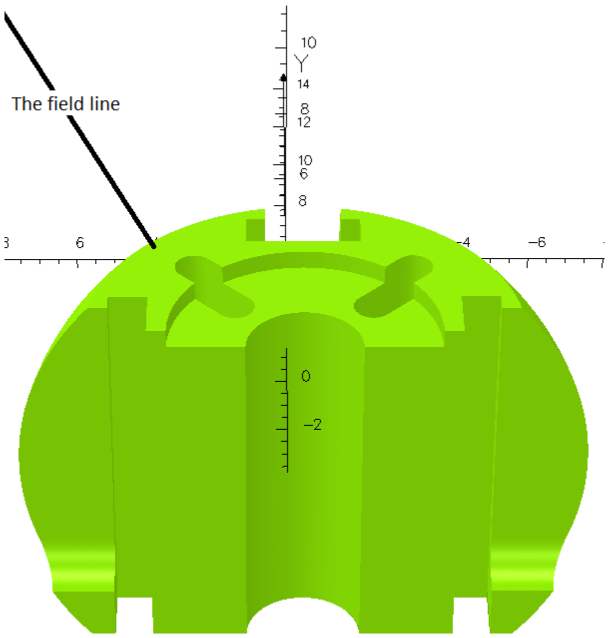


Figure 4.17: New field line.

The field line shown in figure 4.17 is inserted into Matlab and a polynomial is determined like for the previous field line and the polynomial is inserted into the streamer criterion. This results in a K value of 23,12. This K value is close to 18-20 and based on that value the model can be considered accurate to a certain degree. Note should be taken that the edge of the actual sphere that the field line is taken from is also smoother than in the opera model.

Chapter 5

Problem solving

The PD tests that were performed revealed that the connecting sphere from the transformer to the capacitive voltage divider had a corona onset voltage at 114.2 kV. It is decided to construct a new sphere rather then designing a corona screen for the existing sphere. A new sphere will be constructed in the workshop at the university. The radius of the sphere needs to have an sufficiently large radius of curvature so that there will be no corona activity at 200 kV. This will be calculated and presented in the next section.

5.1 Improving the connecting sphere

The exact size of the sphere needs to be calculated based on the voltage that are applied to the sphere. The aim of the project is to be able to raise the voltage up to 200 kV without having any PD activity in the setup. A 10% error margin will be accounted for in the calculations. This means that the sphere will be calculated for 220 kV. This means if a sphere is constructed that has corona onset voltage of 220 kV none will be present at 200 kV. A larger error margin can also be selected e.g. the onset voltage for the sphere could be 250 kV but will result in a larger sphere and more cost in materials. The setup can only reach 200 kV therefore it should be sufficient to base the calculations on 220 kV.

5.2 Sphere calculations

Using Gauss's law the electrical field strength from the sphere can be calculated with 5.1.

$$E(x) = \frac{V}{\frac{R_2 - R_1}{R1 \cdot R2}} \frac{1}{x^2} \qquad [V/cm] \quad (5.1)$$

Where:

- R_1 is the radius of the inner sphere.
- R_2 is the radius of the outer sphere.
- V is the applied voltage.
- x is the distance in cm.

Equation 5.1 explains the relation of the electrical field strength in concentric spheres relative to the distance x from the inner sphere. This is further explained in figure 5.1.

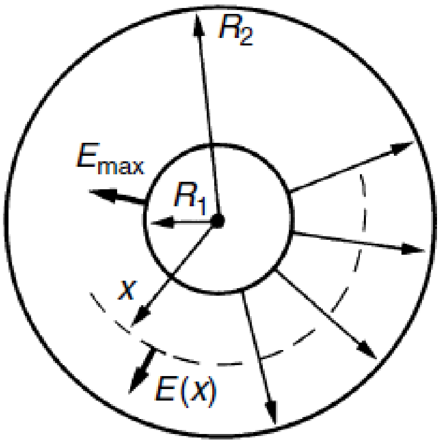


Figure 5.1: Concentric spheres [9].

Figure 5.1 shows concentric spheres and how they are represented by equation 5.1. In the laboratory there is only one sphere or R1 and R2 is represented by the walls of the laboratory. By selecting a sufficiently large outer radius (R2) the outer radius ceases to have an impact on the electrical field from the inner sphere. This is true as long as the ratio of R2/R1 » 1 [9].

Note should be taken that in order to calculate the electrical field with equation 5.1 the peak value of the voltages should be used, not the rms value.

The existing connecting sphere has a radius of 7.5 cm. Therefore a sphere is chosen that has a small increase in radius in relation to the existing sphere. This leads to a sphere of inner radius R1=10 cm, outer radius R2=300 cm and 220 kV rms are selected.

The electrical field strength is then calculated with equation 5.1. From the surface of the sphere to 90 cm. There is no need to calculate all the values to 300 cm or to the radius of the outer sphere. This is because the electrical field strength decays rapidly the further away, the field is, from the inner sphere. The values are then plotted in Matlab and a polynomial that describes the electrical field strength is determined. This is shown in figure 5.2.

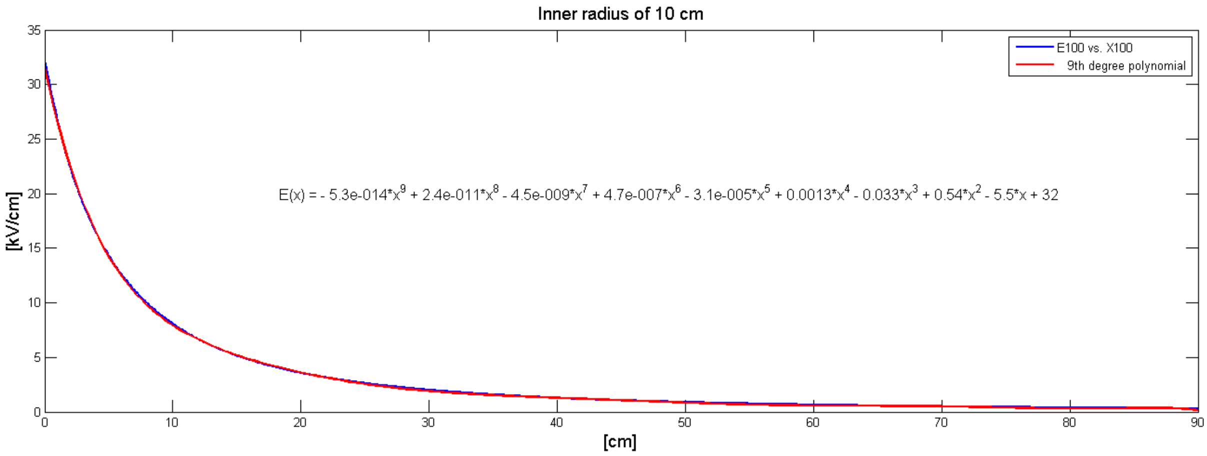


Figure 5.2: The calculated electrical field and its 9th degree polynomial.

In figure 5.2 the calculated electrical field is shown with the blue line and the 9th degree polynomial is shown with the red line. It can be seen that the polynomial is a good match for the electrical field. Furthermore the polynomial equation (E(x)) can be seen in the figure.

The next step is to find the critical x value or X_c for the electrical field E(x) that was found with the help of maple. This is done by taking the 9th degree polynomial or E(x) and making it equal to 24.36 kV and solve for the x value. This results in a value for X_c to be 1.62 cm.

The next step is to insert the known values into Schumanns empiric relation shown in equation 5.2 [9].

$$\frac{\alpha}{p} = C\left[\left(\frac{E(x)}{p}\right) - \left(\frac{E_c}{p}\right)\right]^2 \qquad [-] \quad (5.2)$$

It was explained previously in the report that the air density is considered ideal. Therefore p is set to 1 and other constants in the equation are known. The next step is to use the Townsends streamer criterion shown in equation 5.3.

$$\int_0^{x_c<d} \alpha dx = \approx 18 - 20 = K \qquad [-] \quad (5.3)$$

Equation 5.2 is inserted into equation 5.3 which yields equation 5.4.

$$\int_0^{x_c<d} C\left[E(x) - E_c\right]^2 dx = K \approx 18 - 20 \qquad [-] \quad (5.4)$$

Equation 5.4 is used to calculate if the sphere that was chosen, of radius 10 cm, will be large enough to withstand a voltage of 220 kV rms. The known values are inserted into equation 5.4 and are shown below in equation 5.5.

$$\int_{0}^{1.62388} \frac{18}{45.16}[E(x) - 24.36]^2 dx = K \qquad [-] \quad (5.5)$$

The result of equation 5.5 reveals K to be equal to 11.60 which is less than 18-20 therefore this sphere is to large for 220 kV rms. This was the first guess for the sphere size, therefore the calculations will be performed again with a smaller sphere.

The sphere size that is chosen next is 8.5 cm and the same steps are taken to calculate as before. The results for K will only be presented not the actual polynomial as before. A sphere size of 8.5 results in a K value of 42.12. Based on the calculations a sphere of 8.5 cm is to small, but the size of the sphere lies between 8.5 and 10 cm.

The calculations will be performed until a sphere size is found that results in K to be between 18 and 20. The different sphere sized that are tested can be seen in the table 5.1. Note should be taken that the values for the sphere sizes are in the same order they are calculated not after a numerical order.

Sphere size calculations	
Inner radius	K value
10 cm	11.60
8.5 cm	42.12
9 cm	27.05
9.5 cm	16.30
9.3 cm	19.59

Table 5.1: Calculated K values from the streamer criterion for different sphere sizes.

Based on the above table 5.1 a sphere radius of 9.3 cm gives a K value of 19.59 which fulfills the criteria of having K between 18-20. Figure 5.3 shows the electrical field strength for a sphere of 9.3 cm and its polynomial used for the calculations is also shown in the figure.

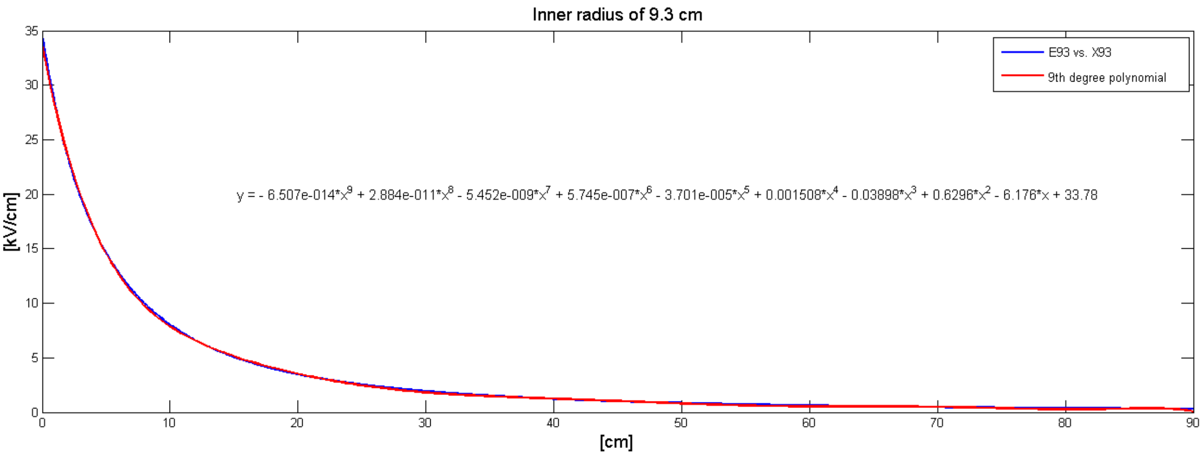


Figure 5.3: The calculated electrical field and its 9th degree polynomial.

Based on the above findings a sphere of 9.3 cm is sufficient to raise the voltages up to 200 kV rms without having any PD activity in the sphere that connects the transformer to the measuring capacitors. The sphere will be constructed in the university workshop.

5.3 Sphere design

After the radius of the sphere had been calculated the sphere has to be designed and built at the University workshop. The sphere should replace the existing connecting sphere and it should fit on top of the capacitive voltage divider. In figure 5.4 is the top of the capacitor where the connecting sphere will be placed.

Figure 5.4: The top of the capacitor.

The sphere design, that was calculated in the previous section, is shown below in figure 5.5.

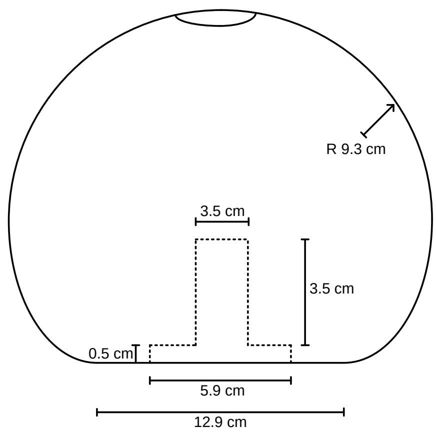


Figure 5.5: The new connecting sphere.

The dotted lines represent that the sphere is hollow to some degree so it can be placed on top of the voltage dividing capacitor like shown in figure 5.4. The bottom of the sphere has also been made flat. The diameter of the bottom is the same as the diameter of the capacitor the sphere is placed on top of. This is so that the sphere will sit on top of the capacitor in the same manner as the old connecting sphere. Further more there is a small dent in the top of the sphere this is done to connect the sphere to the transformer. The standard connecting equipment can not be used to connect the sphere to the transformer. Therefore a rod, of the same diameter as the one that connects the transformer to the coupling capacitor will be used to connect the sphere.

5.4 The modified setup

After the construction of the new connection sphere, the same PD measurements will be performed again to see if there is any improvement on the PD activity of the setup. A figure of the new connecting sphere can be seen below 5.6.

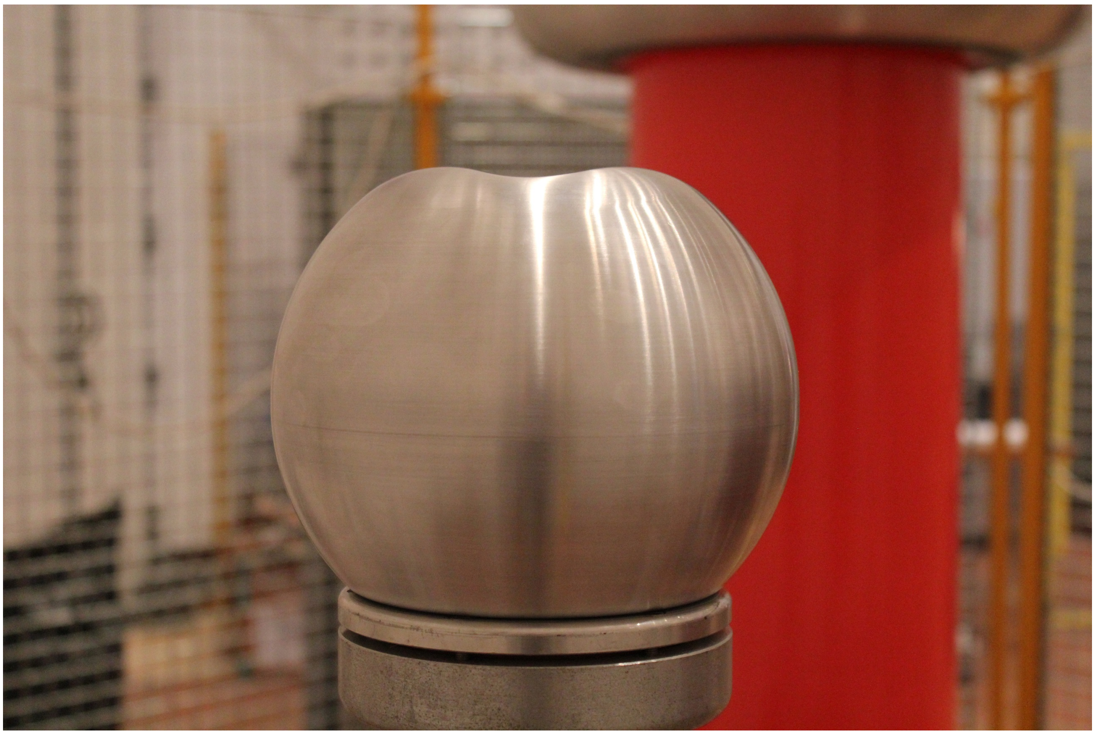


Figure 5.6: The new connecting sphere constructed at the university workshop.

The setup needs to be modified further because the previous connecting sphere was connected to the transformer with the standard connecting rod. This rod can not be used for the new sphere therefore a new connecting rod was constructed. The new and old connecting rods can be seen below in figure 5.7.

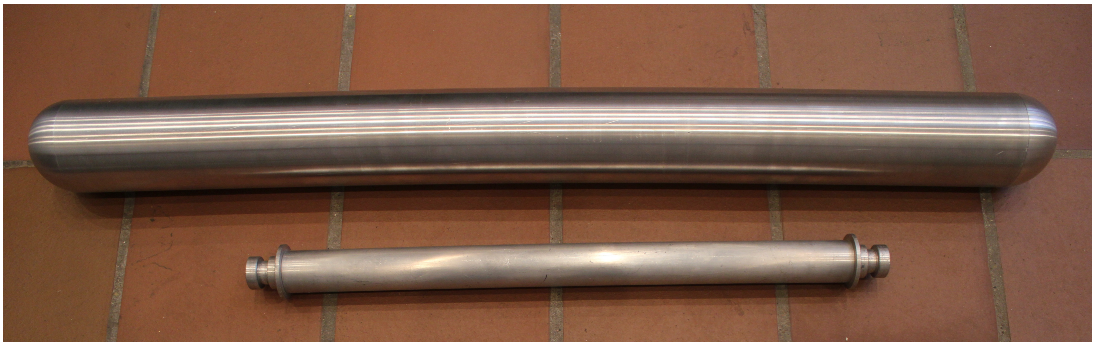


Figure 5.7: The two connecting rods.

The total setup with the modifications that where made can be seen in figure 5.8.

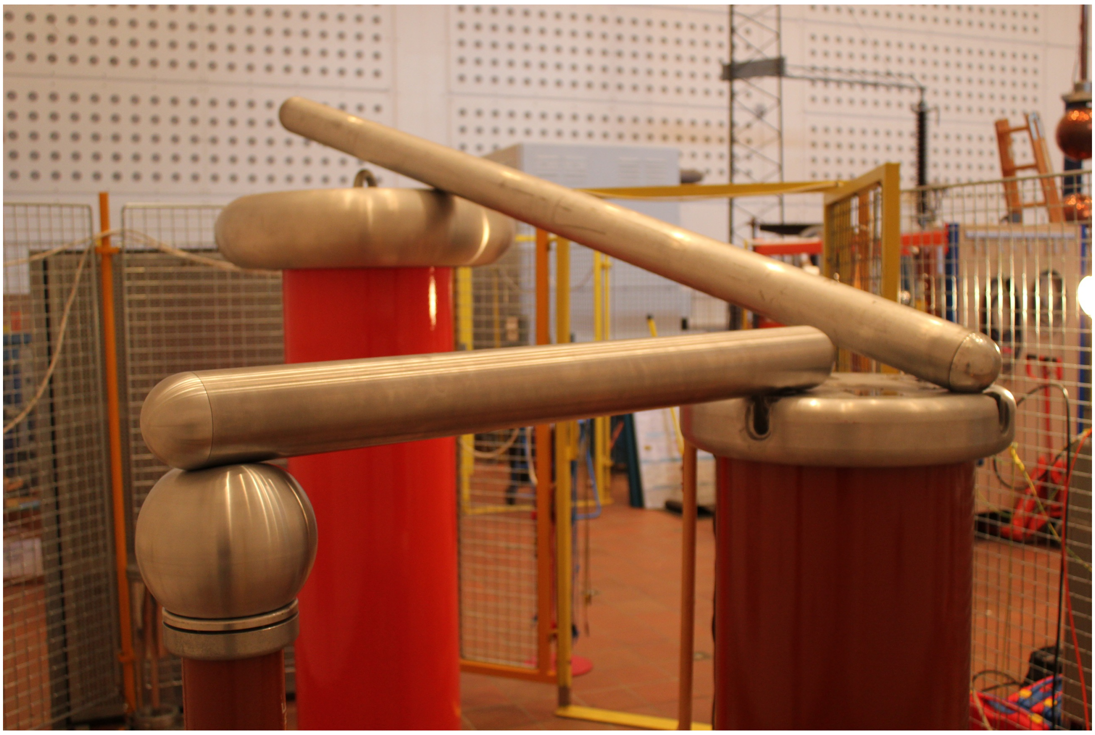


Figure 5.8: The setup after the modifications.

Note should be taken that in figure 5.6 that the top of the sphere has a little crew in it that is so the connecting rod can sit on top of the sphere. Furthermore the new rod has the same diameter as the existing rod from the transformer to the coupling capacitor. The rod should not have any corona activity present.

5.5 Partial discharge testing of the modified setup

The partial discharge test will be performed in the same manner as the previous PD tests that was performed at the laboratory. The first test that is done is to see at what voltage level the corona onset voltage is. The omicron first detects PD activity at 149.3 kV. The results are shown in figure 5.9.

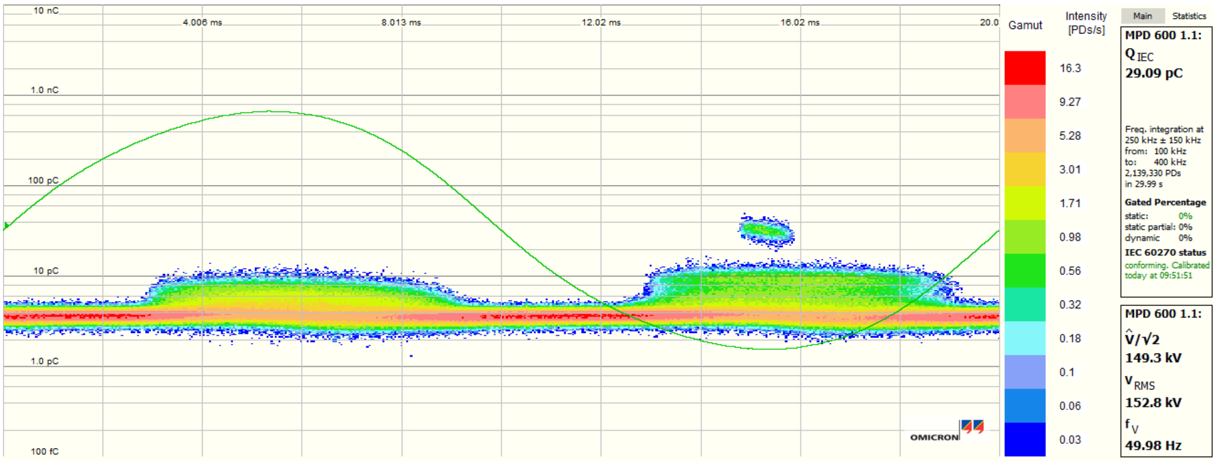


Figure 5.9: Results of the first PD test.

The results of the first test show that the only the transformer shows corona activity. The profile has the same characteristics as in the previous test where the voltage divider was disconnected. For comparison a figure of the first test will displayed again below in 5.10

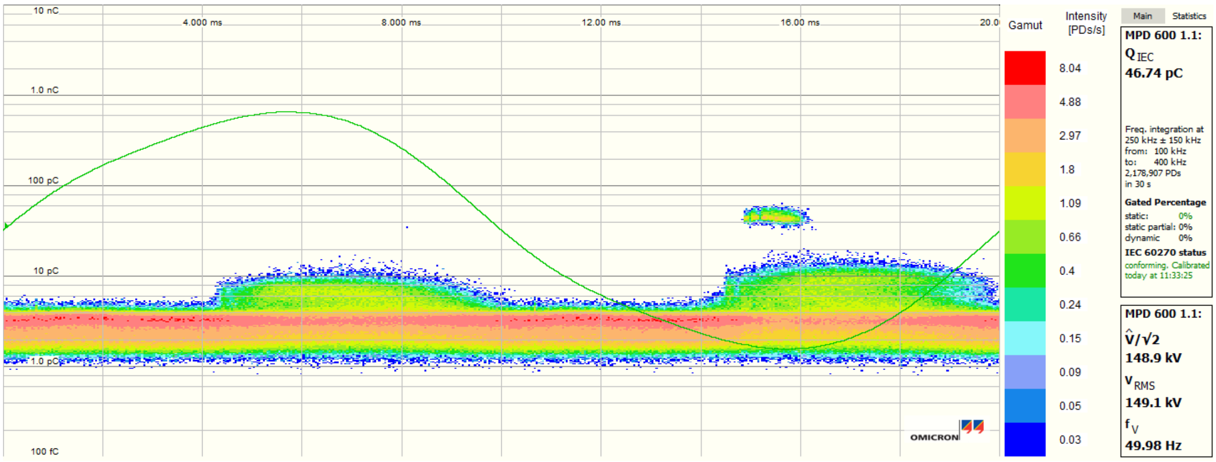


Figure 5.10: Results of the PD test with the measuring capacitor disconnected.

It is apparent that figure 5.9 and 5.10 do have the same PD profile and the onset voltage is the same for both results. It is further confirmed with the ultrasound detector that the source of the PD activity is the transformer. During the test no sound was detected with the ultrasound detector from the connecting sphere.

The next test that is performed is to raise the voltages up to 200 kV and see if there is any corona activity on the connecting sphere. The Omicron device can not distinguish where on the setup the corona is formed. Because the transformer has a corona onset voltage of 149 kV the omicron device can not be used to determine if there is corona on the new connection sphere. Therefore the ultrasound detector, and visual conformation will be used to determine if there is corona in the connecting sphere.

The voltages are increased to 150 kV and then slowly increased to 200 kV while listening with the ultrasound detector. No sound was detected on the connecting sphere during the test. Even though the Omicron device can not be used to determine where the PD activity is coming from, a figure of the test results are shown in figure 5.11

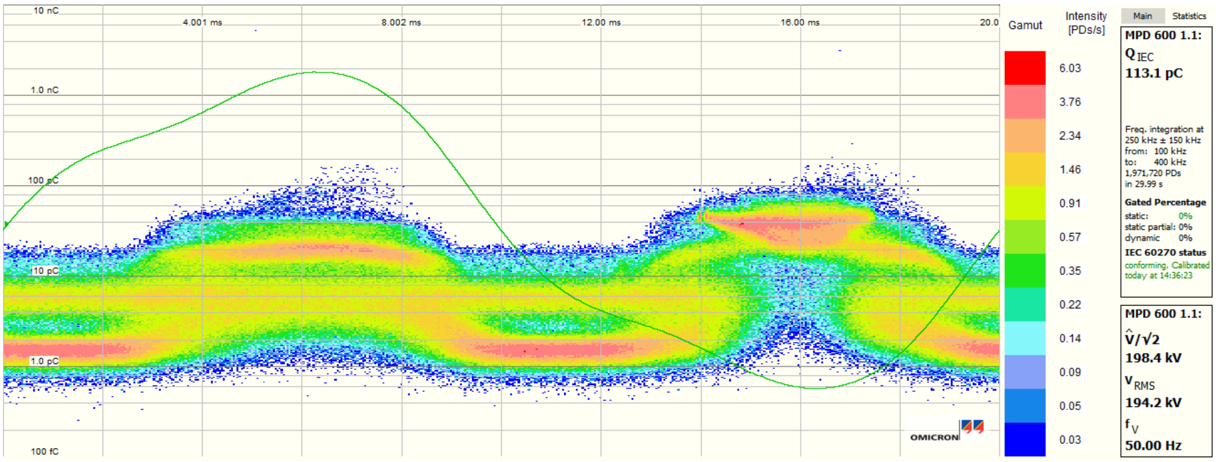


Figure 5.11: Results of the PD test at 200 kV.

It is apparent from figure 5.11 that the PD activity is corona both positive and negative. The profile of the PD activity is similar to the previous test in figure 5.9. But the PD pulses are spread over a wider range ranging from around 1 pC to 113 pC. It is also interesting to see the voltage curve at 200 kV. The sinusoidal wave is deformed, because of transformer saturation [1]. That seems to have some influence on where the PD pulses appear in figure 5.11.

A visual test is also performed at 200 kV to see if there is any visible corona on the connecting sphere. The visual test is done in the same manner as before by turning off the light and closing the drapes in the high voltage laboratory. The only visible corona was on the transformer like in the previous tests.

5.6 Test conclusion

Based on the previous tests that where performed it is apparent that there is no corona at 114.2 kV for the new connecting sphere, like there was for the previous one. At the transformer corona onset voltage of 149 kV there where still no corona in the connecting sphere. Due to the fact that the omicron device is not able to distinguish where on the setup it measures PD activity, two other methods where used to validate the connecting sphere. By using the ultrasound detector no sound where present at 200 kV from the connecting sphere and no visible corona was detected at 200 kV apart from the transformer.

Based on the above measurements it is assumed that the sphere calculation and design of the sphere in 5.2 where successful.

Chapter 6

Conclusion

The focus of the report was to reduce the amount of corona in the high voltage setup available in the laboratory. In order to do that a series of tests where performed, both in the laboratory and via a computer model.

Based on the partial discharge tests that were performed in the laboratory, it was determined that the connecting sphere had a corona onset voltage of 114.2 kV. The top electrode of the transformer has a corona onset voltage of 149 kV. Due to the lower corona onset voltage of the connecting sphere compared to the transformer, it was selected as the focus point to increase the corona onset voltage or eliminate it altogether.

A visual test of the corona was furthermore performed in the laboratory. This was performed in order to see where on the connecting sphere and in what direction the electrical field is strongest.

A finite element model of the connecting sphere was constructed in the Opera3d FEM program. The connecting sphere in the model was given the same voltage value as the spheres onset voltage, which was determined during the PD testing. The objective of the FEM model was to verify the corona onset voltage of the connecting sphere from the PD measurements. This was achieved by studying the field strength at the same location and direction determined during the visual test in the laboratory. A field line was drawn from the connecting sphere in the model. The field line was calculated using the steamer criterion to see if there is corona at the chosen location.

The results for the model showed that there is corona at the chosen location, but the value calculated for the K constant proved to be, 42 which is more than double the desired value of 18-20. The expected results from the model was a K constant a little over 18-20. This is due to physical difference on the connecting sphere in the model and the sphere in the laboratory. The sphere in the model has sharper edges than the one in the laboratory, which results in a higher electrical field strength. The difference can also be that the mesh size is to large, resulting in inaccurate electrical field strength. A second field line was drawn from the connecting sphere. This field line resulted in no corona activity in the laboratory. This field line gives a K constant of 23 which is a little over 18-20. A previously stated the modeled sphere has sharper edges at this location than the connecting sphere in the laboratory. Considering the edges and the K constant of 23 the model can be considered accurate. If the edges of the model, for the second field line, where made smother like the sphere in the laboratory the field strength would be less at that location. Resulting in the K value to go under 18-20.

The sphere that was designed and constructed at the university has a very smooth and uniform surface, unlike the previous connecting sphere. The first test that was performed in the laboratory with the new sphere was to see at which voltage level the Omicron device would first measure PD activity. The Omicron first measured PD activity at 149 kV which was the top electrode of the transformer. This shows that the new sphere has no corona at that voltage level and it has surpassed the previous onset voltage of 114.2 kV. Due to the limiting factor of the Omicron device not being able to determine where on the setup it measures PD activity. Therefore the ultrasound detector will be used to determine if there is corona on the new connecting sphere at 200 kV. The voltage where raised slowly from 150 to 200 kV with the ultrasound detector pointed on the connecting sphere. No audible sound where detected from the connecting sphere at 200 kV. A visual test is also performed at 200 kV and no visible light came from the connecting sphere, only the transformer.

Even though the Omicron device can not be used to verify that the sphere has no PD activity at 200 kV, there where no audible noise coming from the sphere with the ultrasound detector. Based on that the sphere calculation and design is considered successful as no corona was detected at 200 kV. Furthermore the new connecting sphere reduces the amount of corona present in the setup.

Chapter 7

Future work

This project focused on reducing corona in a high voltage test setup. To further improve the test setup at Aalborg universities high voltage laboratory, would be to look at the top electrode of the transformer. If the top electrode of the transformer could be improved to have no corona at 200 kV. Then the designed sphere could be verified with the Omicron device. To improve the corona onset voltage of the transformer some sort of a hat or a corona screen would be constructed, that is placed on top of the transformer.

It could also be looked into the possibility of having a device that can pin point the exact location of a PD measurement with the Omicron device. If that is possible than the sphere could be verified with out changing the top electrode of the transformer.

In regards to the finite element model some improvements could be made with the mesh size of the model. Having a smaller mesh size would give better results, but in order to have a smaller mesh size a more powerful computer would need to be available. The connecting sphere in the FEM model could also be improved by smoothing out the edges of the model so it would give a better representation of the actual connecting sphere.

Appendix

Appendix A

Additional figures of the test setup.

In this appendix additional figures of the connection sphere can be seen in figures A.1, A.2, A.3 and A.4.

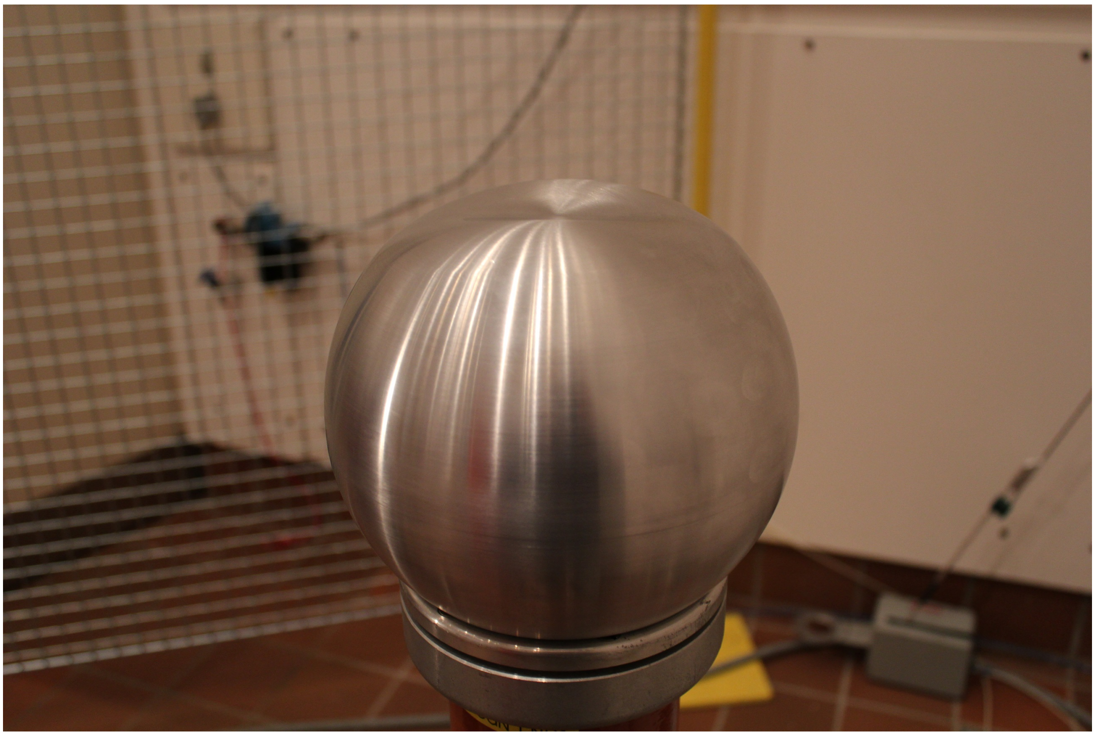


Figure A.1: The connection sphere.

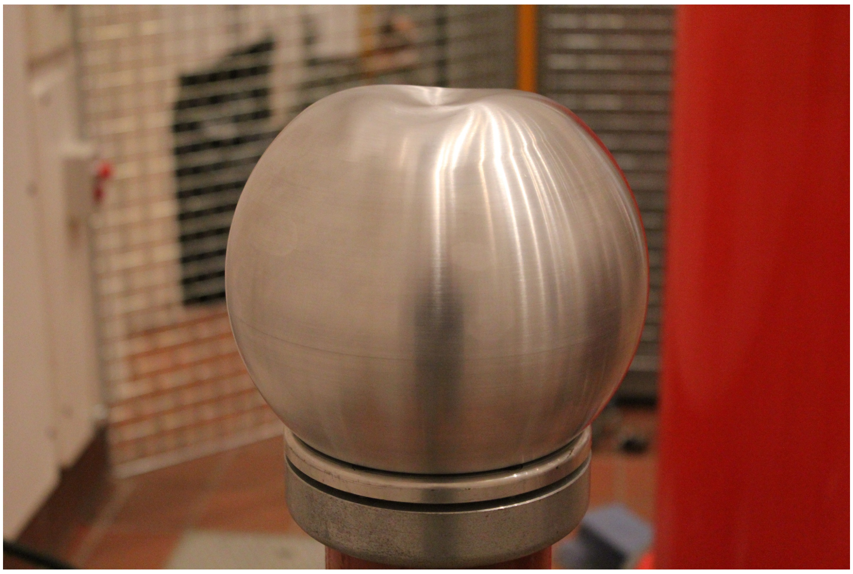


Figure A.2: Different view of the connection sphere.

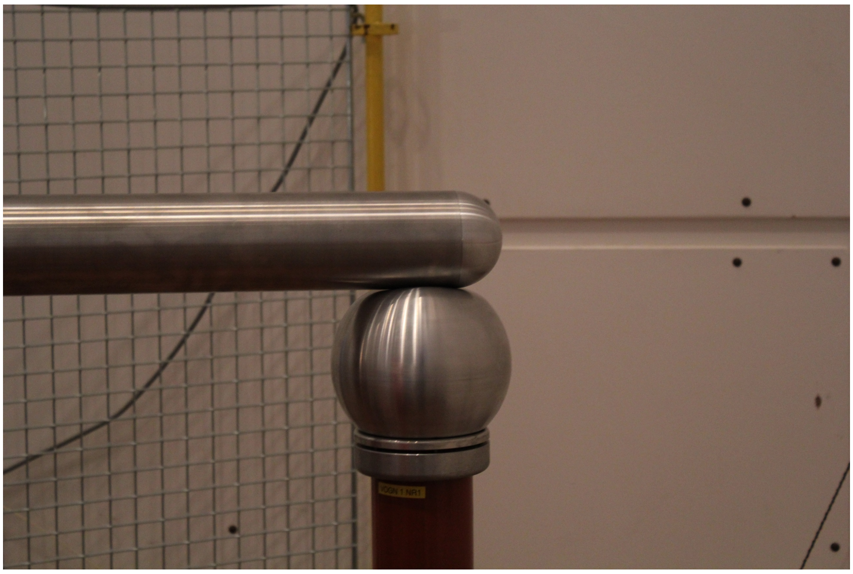


Figure A.3: The connection sphere with the rod.

Figure A.4: The connection sphere ontop of the voltage divider.

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