Analysis of Partial Discharge in OIP Bushing Models

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Abstract

A high voltage bushing is a very important accessory of power transformers. Bushings are used to insulate high voltage conductors where they feed through steel tank of a power transformer. There are different sources of electric stress that may result in degradation of bushing. Partial discharges (PDs) are one of the main sources of electrical degradation. PDs occur due to defects in electrical insulations, and can lead to insulation failure. This thesis is composed of two parts. The first part deals with design of a 145 kV oil impregnated paper (OIP) bushing by using capacitive radial grading technique. In capacitive grading the foils of calculated length are placed at predetermined radial distance between the paper layers in order to distribute voltage and electric field uniformly between high voltage conductor and ground potential. A 145kV OIP bushing was designed according to dimensions of ABB GOE type bushing. After calculations, the 145 kV bushing geometry was modeled in COMSOL Multiphysics in order to analyze the voltage and electric field distribution in the bushing. In the second part of this thesis a scaled down model was designed using the capacitive radial grading technique. After designing, the scale down model was implemented in COMSOL in order to ensure that the voltage and electric field distribution should be similar to the full scale model of bushing. The scaled down bushing test model was made in laboratory by wrapping impregnated papers and foils on conductor tube according to calculated dimensions. These papers were impregnated with mineral oil. The test model was placed in an oil filled tube. Different defects were added in scale down bushing model and model was connected to PD measurement set up. PD inception voltage was measured and PD patterns were recorded on an insulation condition monitoring system (ICM). These patterns are analyzed in order to conclude about the signature of partial discharges in OIP bushings. From the PD pattern, the type and location of PDs can be concluded. PD patterns reveal that the main causes of PDs in OIP bushing can be gas filled cavities and surface discharges from foil edges.

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Zeeshan Ahmed

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Abbreviations

AC	Alternating current
DC	Direct current
PD	Partial Discharge
OIP	Oil Impregnated Paper
RBP	Resin Bonded Paper
RIP	Resin Impregnated Paper
CMPH	COMSOL Multiphysics
ICM	Insulation Condition Monitoring
DAP	Data Acquisition Processor

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1 Introduction

1.1 Background

Energy is the major requirement for the development of any country. Energy exists in different forms but the most important form is electrical energy. Nowadays, countries economic development is dependent on availability of electrical energy as industrial production, health facilities, agriculture, household electronics machineries and even transportation facilities are now dependent on availability of electrical energy. The modern day life is so much dependent on electrical energy that it is not affordable to have outage of electricity even for few minutes.

Electric power system has three main components

- Generation
- Transmission
- Distribution

Three phase AC system with operating frequency of 50 Hz or 60 Hz is used for generation, transmission, distribution and utilization of electricity. Transformers are used for raising or lowering ac voltage with the same frequency. Transformers are very important equipment in a power system network.

A transformer is a static device that transfers electrical energy from one circuit to another circuit without change in frequency by electromagnetic induction. It consists of a magnetic core made up of silicon steel lamination and a set of coils wound on core which are termed as the primary winding and secondary winding. The electrical energy received by primary winding is converted into magnetic energy which is again converted back into electrical energy in the secondary winding. Both windings are magnetically coupled. Transformer is named as step up when secondary voltage is higher than primary voltage and it is named as step down when secondary voltage is lower than primary. Step up transformers are used in generating station as high voltage is required to be transmitted. Step down transformers are used in transmission, distribution network so that loads can operate at their desired level. Primary and secondary voltage is dependent on number of turns. [1]

The major parts of transformer are core, windings, oil, insulation system for windings, steel tank, etc. Large power transformers in generating stations have same components but additional components are tap changer, separate cooling system and they have modified core. In transformers oil can be used as coolant. [2]

Transformers in generating stations are characterized by the following characteristics

- Large size and high transport weight
- High MVA and kV ratings
- Long bushings
- Separate installed coolers with forced air and forced oil cooling

- Three or five limb construction

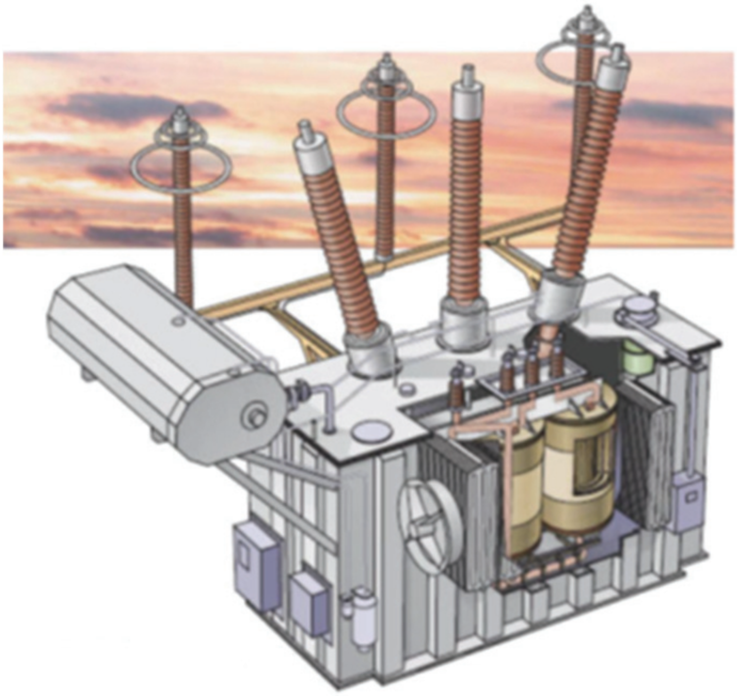

Figure 1.1 Structure of power transformer [3]

The Bushings and tap changer are the most important accessories of a transformer, but this project is focused on bushings. The bushings are used to insulate high voltage conductors through a steel tank. In large power transformers the high voltage conductors are required to transmit the high power to long distances so conductors are connected to the winding terminals of power transformer and for the passage of these conductors the bushings are used. The material used in the bushing must have high dielectric strength and sufficient mechanical strength to support the conductor and anything attached to the conductor. Electrical power is the product of voltage and current so bushing material must be capable of withstanding high voltage and conductor must carry current without overheating so that it cannot damage the insulation. Bushings are rated by a maximum voltage and current instead of power transmitted through them.

In high voltage bushing construction, for the inner core insulations oil impregnated paper (OIP) and resin impregnated paper (RIP) can be used and porcelain insulation is used for housing the bushing. Nowadays silicone rubber housings are also used in oil to air applications. The bushings with silicone rubber housing have high elasticity and high strength against mechanical stresses and shocks.

It is clear from Figure 1.1 that the insulation is used both inside and outside of power transformer. The portion of insulation in the form of rings outside the power transformer is called bushing which is connected to winding terminal inside the power transformer not shown in this figure.

In this project bushings are discussed in detail in Chapter 2. Different types of bushing are explained. Bushing is very important accessory of power transformer therefore it must be checked in regular interval of time and different tests are performed according to international standards in order to ensure that the bushing is working correctly, because if the bushing is damaged it can result in big failure as it is insulation for power transformer which is very important component of power system. Bushing must be able to withstand the following stresses.

- Electrical stress
- Mechanical stress
- Thermal stress
- Ambient stress

There are different sources of electrical stress that results in degradation of insulation material.

- Partial Discharge
- Electrical tree
- Depolymerization
- Increased moisture

Partial discharge (PD) occurs as a result of defects in the insulation system. There are two types of breakdown in insulations stressed by high voltage applications. In complete breakdown insulation is completely bridged between the electrodes by low ohmic resistance. During incomplete breakdown only a small portion of insulation is collapsed because of high local electric field stress and healthy portion is still withstanding high voltage stress. It is also termed as a partial discharge.

When the electric field in the defect exceeds the threshold field it results in partial discharge [4]. There are different types of partial discharge, e.g. surface discharge, gliding discharge, internal discharge and corona discharge. Partial discharge can take place in all medium of insulations. It can take place in mixed insulations also. The main sources of partial discharges are voids, cavities, gas bubbles in liquid insulation or solid liquid insulation and sharp particles or edges in insulation. When partial discharge take place in liquid impregnated papers it can also generate gas bubbles that further produce partial discharge. Corona is different from other types as it is visible and creates hissing sounds. Discharges occurs in gas filled voids and gas bubbles because the gas has lower dielectric constant than the material surrounding the voids if the electric field is high enough to ionize the gas it results in electric breakdown of gas. Surface discharges occur when tangential electric field is high enough to cause electric breakdown on surface.

In this project the signatures of partial discharges (PDs) are analyzed on OIP bushing models. There are other important phenomenas that can be analyzed in bushings for example power factor measurement, capacitive measurement, loss factor measurements, depolarization measurements etc. but this project is focused only on partial discharge. Partial discharge (PD) is already analyzed in detail regarding solid insulation inside the transformer, motor insulations and in transformer oil by many researchers. But nowadays, the development of high power density equipments has increased the electric stress on bushings therefore the analysis of signature of partial discharge in bushing must be done for economic and safety reasons. The analysis of partial discharges in bushings can help the designers to remove the causes of defects during design and manufacturing stage. It can help to increase the life span as PDs result in degradation and ageing of bushing.

1.2 Ongoing research

The partial discharge is a very interesting phenomenon in electrical insulation studies. Many international research papers are written on a partial discharge in oil impregnated paper bushing. The partial discharge analysis is used to assess the ageing process of oil impregnated paper bushing. By applying the voltage surges the ageing of OIP bushing models and the effect of voltage surges on creation of gas bubbles can be analyzed. The faulty impregnation of papers and gas evolution in oil impregnation papers during electric stress also results in occurrence of the partial discharge which is one of the main reasons for accelerated ageing of bushing [5]. The oil impregnated papers are covered with mineral oil therefore the gassing tendency of mineral oil is very important phenomenon in analysis of partial discharge. The ongoing research in the partial discharges reveals that the gas bubbles in mineral can be the cause of partial discharge but the PD pattern is not stable as the gas bubbles disintegrate in oil therefore gas bubbles in oil are not main source of PDs in bushings. The inception voltage measurement shows the minimum voltage required to start PDs. The inception voltage variation with thickness of insulation is clear from ongoing research in this field. Nowadays partial discharge measurement technique is given priority by many researchers. Most of the high voltage laboratories are still using narrow band detection test setup for partial discharge measurements, but this test setup has some limitations as the PD pattern is ascending and descending with applied voltage and the oil impregnated paper bushings exhibit the pulse burst phenomenon in PD patterns therefore the narrow band detection systems cannot detect all the pulses in one pulse burst. It considers the burst pulse as one pulse whereas by using the wide band of 500 MHz or more it is possible to detect all pulses [6]. Gassing phenomenon is already analyzed in detail regarding oil impregnated paper insulation in detail as this insulation is used for different electrical equipments.

1.3 Aim

The specific objective in this thesis is to investigate the following.

- Propose a model of a 145 kV OIP bushing in COMSOL Multiphysics (CMPH) [7] that gives close resemblance to calculated dimension of OIP bushing and to investigate the voltage distribution between foils and electric field stress in bushing.
- Propose a scaled down model which should have almost same electric stress and uniform voltage distribution between foils as in 145 kV full scale model of bushing
- Manufacture scaled down model in high voltage laboratory.

- To investigate the signature of partial discharge in OIP bushing by deliberately introducing defects in the scale down test model.

1.4 Method

- The OIP bushing was selected from ABB GOE type data sheets.
- The 145 kV OIP bushing model was designed using capacitive radial grading technique. In this technique spacing between foil is constant and length of foil is calculated by using the previous foil length. The capacitance between foil is assumed constant.
- The 145 kV bushing model was proposed in the CMPH. The geometry was created on CMPH. The boundary conditions and subdomain conditions of designed model were set in CMPH. The voltage distribution and electric field stress was analyzed in CMPH after solving the model.
- The scaled down model was designed using capacitive radial grading technique and model was proposed in CMPH which should have almost same electrical stress and uniform voltage distribution as in 145 kV full scale model. Only the core insulation was considered in scaled down model.
- The scaled down test model was set in the laboratory by wrapping papers and foils on conductor tube according to selected dimensions. The papers were impregnated with mineral oil in laboratory. The test model was placed inside the oil tube. The last foil was grounded by connecting it to conducting wire and taking it out through small hole in tube which was then connected to earth wire. The defects were deliberately introduced in test model in order to analyze the signature of the partial discharge.
- The test model setup was connected to partial discharge measurement setup. The PD measurement setup was divided into a high voltage part and a low voltage part. The high voltage part included variable transformer, step up transformer, capacitive potential divider, coupling capacitors. The scale down model was connected to high voltage part. The low voltage part included computer, oscilloscope, detection impedance, preamplifier and insulation condition monitoring (ICM) system [8]. The voltage was controlled from knob bench. PDs were observed on oscilloscope and inception voltage was measured at which the repetition of PDs started. After measuring inception voltage the PD pattern was recorded on ICM system and the patterns were extracted from ICM files by using MATLAB code. In the end of this report results are analyzed.

2 High voltage bushing

The high voltage bushing carries one or more high voltage conductors through an earthed barrier such as a metal tank. It must provide electrical and mechanical support to apparatus for which it is used. It provides insulation at rated voltage and overvoltage conditions. It also serves as mechanical support to high voltage conductor and other external connection. The bushing must have high dielectric strength [9, 10].

2.1 Types of bushing

The bushing can be classified on the basis of surrounding medium at its ends, according to its construction and according to the insulation inside the bushing [9].

2.1.1 Based on insulating media on ends

2.1.1.1 Air to oil bushings

An air to oil bushing has air at one end of the bushing and oil at the other end. Oil is dielectrically stronger than the air at normal pressure so the oil end is shorter than the air end. This type of bushing is used in situations where oil filled apparatus is in contact with air [9].

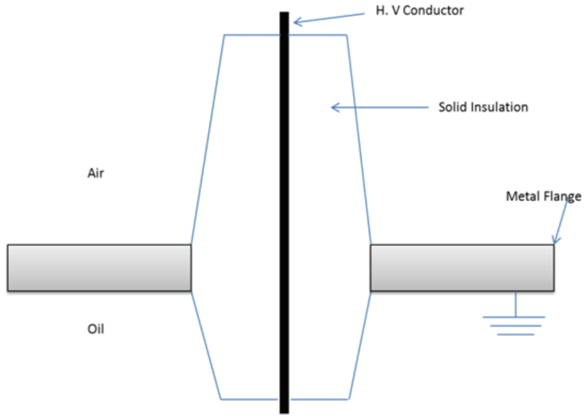

Figure 2.1 Air to oil bushing

2.1.1.2 Air to air bushings

An air to air bushing has air on both ends and is used in situations where apparatus is exposed to outdoor air at one end and the other end is exposed to indoor conditions. The outdoor side has higher creep distance as it is exposed to high pollution environments, and it also has to withstand high transient voltages in severe weather conditions such as lightning, rain etc. [9].

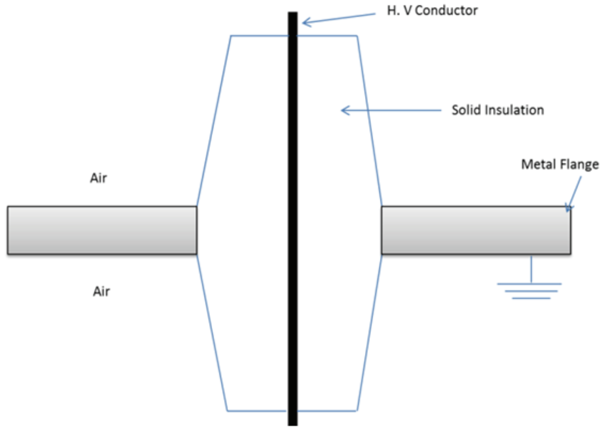

Figure 2.2 Air to air bushing

2.1.1.3 Special bushings

There are special bushings e.g. SF6 to air bushings in which SF6 is involved at one side and air is on other side such as SF6 insulated circuit breakers or oil to oil bushings between oil filled apparatus and oil filled bus ducts [9].

2.1.2 Based on construction

There are two types of bushings based on construction

2.1.2.1 Solid type bushing

The solid bushing consists of single conductor in center and porcelain or epoxy resin insulators at both ends and it is used for lower voltage. These bushings are used for small distribution transformers and circuit switches for power transformers. At lower voltages central conductors can be connected directly to transformer winding and the conductor can be small diameter lead which passes through bore in porcelain. At higher voltages it is important that the lead and bore of insulator are concentric and circular such that the electric stress in gap is under controlled and uniform. The diameter of copper lead is increased for higher current rating bushing typically up to 20 kA. The space between lead and porcelain or epoxy is filled with either air or mineral oil depending on the voltage rating. For lower voltage air is used and for higher voltage bushings the electrical graded mineral oil or any special compound is used in space between lead conductor and solid insulation. The oil can be self-contained and or less likely it can be from the apparatus for which the bushing is used. Oil is used because it is better coolant than an air and it has higher dielectric strength than air so it can withstand higher voltage than air [9].

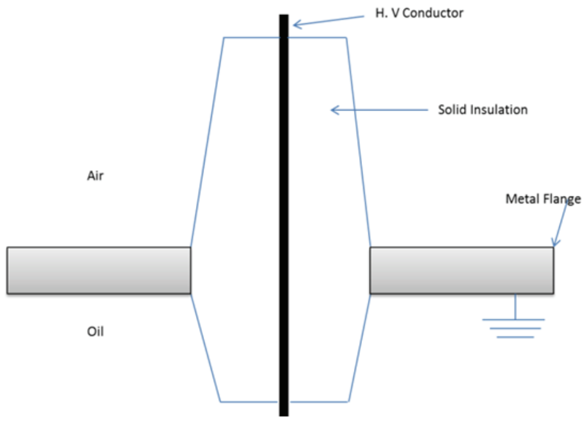

Figure 2.3 Solid type bushing

The solid bushing is good for lower voltages as it is cheaper also, but it has limitation of withstanding 60 Hz voltages above 90 kV. It is used for 25 kV rating electrical equipments [7]. Nowadays requirement of low partial discharge limits during transformer test has put restrictions on usage of solid type bushing. The solid bushing has nonuniform voltage distribution both radially and axially. In the radial direction most of the voltage appears near to conductor and on outer surface most of the voltage is near steel tank, so sufficient length of bushing is required for electric stress to be less than the surface flashover voltage of bushing insulation and large diameter is required so that the stress next to conductor is less than the dielectric stress of the insulation material [10].

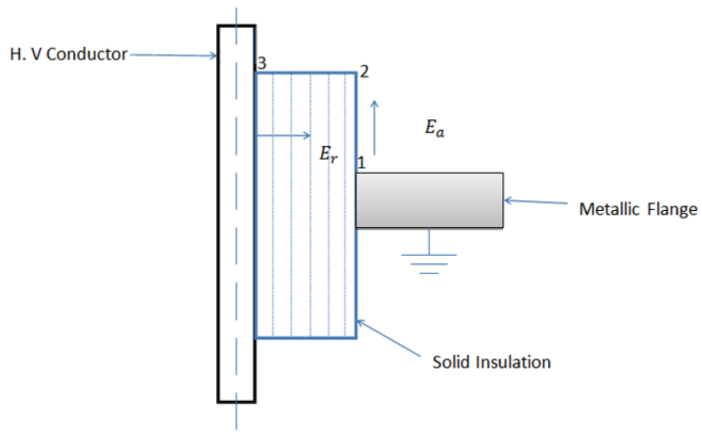

Figure 2.4 Radial and axial electric fields

The radial electric field strength E_r can cause breakdown in insulating material and axial electric field strength E_a can cause surface discharge along the boundary surface. The axial field stress is very critical so proper shaping of boundary must be done. The lower limit for the size of bushing in figure 2.4 can be calculated by [11].

$$U = \int_{conductor}^{ground} E_t \times ds = \int_1^2 E_a \times ds + \int_2^3 E_r \times ds \ldots\ldots\ldots\ldots\ldots\ldots.2.1$$

From equation 2.1, the average tangential electric field E_t and conductor voltage U is calculated. The average value of tangential electric field is calculated by [9].

$$\langle E_t \rangle = \frac{U}{L} \quad \text{............} \quad 2.2$$

L is the length of bushing surface. In order to reduce the dimension of bushing the surface is curved as shown in figure 2.3. The voltage is neither evenly distributed across the radial direction nor along the axial direction. As the voltage increases the dimension also increases therefore the solid type bushing is not feasible for higher voltage applications [11].

2.1.2.2 Capacitance graded bushings

Capacitance graded bushing is also called condenser bushing. In this construction concentric metallic cylinders are added inside the insulation to equalize the potential distribution in the bushings. The potential is equally distributed because the capacitance between the cylinders is equally distributed. In this construction metallic foils are placed at calculated distances in radial direction within oil impregnated papers. The outer foil is connected to a steel tank. The difference in axial length between adjacent metallic cylinders is chosen equal to have equal voltage distribution along the bushing surface. Capacitance graded bushings are usually made of paper insulation. Paper sheets are wound around the conductor until the metallic flange. The metallic foils are inserted between paper layers at predetermined positions to form a series of capacitors between conductor tube and metal flange. In this way the grading foil structure is assembled. The capacitive voltage grading is normally used for voltages above 60 kV. For lower voltages the field control in bushing is done by special electrodes. There are three types of capacitance graded bushings [12].

- Resin Bonded Paper (RBP)
- Oil Impregnated Paper (OIP)
- Resin Impregnated Paper (RIP)

In the synthetic resin bonded paper construction, the papers have resin coating which bonds the metallic layers during heat and pressure in the manufacturing process. Synthetic resin bushing paper has some limitations in length due to paper coating machine capability and its dielectric losses are higher than oil impregnated paper bushing which results in limitation in radial thickness by thermal instability. The RBP is a laminate of resin and paper so the bushing has air distributed between paper fibers and at the edges of metallic foils. RBP type bushings are designed for radial stress of approximately 20 kV/cm [10]. Partial discharge occurs at layers ends where the stress is greater than the radial stress between layers. During production weak resin bonding can produce voids in insulation that can result in PD. Both forms of discharges can lead to failure of the bushing [12].

In an oil impregnated paper bushing the papers are vacuum, dried and soaked in a tank of pure mineral impregnated oil. In the case of long oil impregnated paper bushing, papers can be wound as spiral tape. Selection of number of foils and location is chosen such that the dielectric stress is within the limit of dielectric breakdown of insulation [10]. If OIP bushing is carefully processed then there will be no gas cavities in the bushing therefore the partial discharge inception voltage will be higher than the RBP bushing. The OIP bushings are designed to operate at radial electric field stress of 45 kV/cm [12]. It is necessary to compute the electric stress because discharges at the end of foils result in failure of the bushing. Due to misalignment of conducting layers, discharges can occur at layer ends. Electric field stress is higher at these points and if it is maintained for some time it can result in gassing of oil and dryness of paper which can lead to breakdown [12].

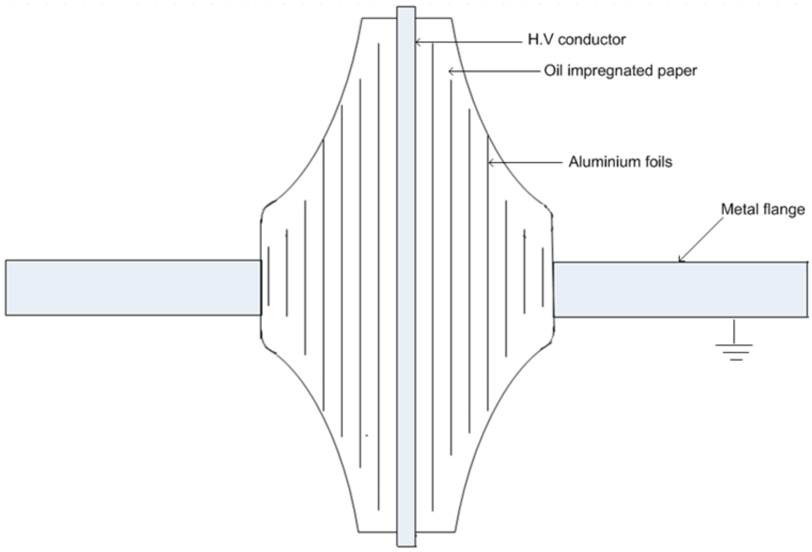

Figure 2.5 Capacitive graded bushing

The length and diameter of grading metallic foils are chosen such as to create a more uniform radial voltage distribution as compared to solid bushing.

RIP bushing was developed in 1960s. Earlier it is used for insulated bus bar system and distribution switchgears. But now it is used for 800 kV systems [12]. In manufacturing of RIP bushing, paper tapes or sheets are wound onto a conductor and conducting layers are placed at predetermined locations in order to control the electric field stress. It is then passed under controlled heat and vacuum. In the end epoxy resin is filled in the bushing. The spacing between layers is variable. RIP bushing is gas tight, void free and dry so it has low dielectric losses and no PDs. It can operate at radial stress of about 36 kV/cm [12].

2.1.3 Insulation inside bushing

Bushings can be classified on the basis of insulating material inside the bushing. These materials are used in both solid type and condenser type bushings [12]. To solve the problems relating to bushings, insulating material is a very important consideration because it can leads to different solutions. For an operating voltage of about 25 kV the bushings are made of porcelain or cast resins and for higher voltages soft papers or hardboards are used with porcelain housing [9]. For example if porcelain is used as insulating material then in order to control the partial discharge the conductive coating is provided inside the porcelain under the metal flange by metal spraying or the clearance between metal flange and porcelain is provided. In case of cast resin the shaft and conducting tube is directly embedded and to avoid the gliding discharge the electrode is embedded in insulation. The capacitive grading bushing is also dependent on insulating material [13].

2.1.3.1 Air insulated bushings
These are used in air insulated apparatus and solid type construction where air is used in between conductors and insulators.

2.1.3.2 Oil filled bushings
Oil filled bushings have graded mineral oil between conductor and insulators in solid type bushing. This oil is either from apparatus where the bushing is installed or oil is separately placed inside the bushing. OIP bushings use mineral oil and impregnated papers between metal foils. Mineral oil is also used for transferring heat from central conductor [9].

2.1.3.3 Oil impregnated paper insulated bushings
Dielectric strength of mineral oil and electrical grading of papers produce a material with better dielectric characteristics. It is used in condenser bushing for last half century.

2.1.3.4 Resin bonded or impregnated paper insulated bushings
Resin bonded paper insulated bushings use to fabricate the capacitance graded core and paper is impregnated with resin in resin impregnated paper insulated bushing**.**

2.1.3.5 Cast insulation bushings
This type of bushing is constructed from solid cast material either with or without inorganic filler. Such a bushing can be implemented in solid type or capacitive graded bushing [9].

2.1.3.6 Gas insulation bushings
These bushings use gas as insulation in between central conductor and metal flange e.g. SF6. Such bushings are used in circuit breakers. It uses the same pressurized gas as circuit breakers. These bushings use the ground shield to control the electric fields instead of capacitive grading [9].

2.2 Bushing standards
There are many bushing standards in the world but the major standards are developed by international Electrical Power engineering society IEEE and by IEC committee. Few major standards established by these organizations are given below [9].

- IEEE standard C57.19.01 is used to standardize the characteristics and dimensions for outdoor power apparatus bushings [14]. This standard is used to give requirements of test voltage for power bushings rated between 15kV and 800 kV. These standards give the dimensions of bushings, cantilever test requirements for bushing, partial discharge limits, power factors, capacitance change before and after standard electrical tests.
- IEEE standard. C57.19.03 is used to give standard terminology, test procedure and requirements for bushings for DC applications [15]. It gives information about the air to air DC bushings. It gives bushing information for direct current equipment like smoothing reactors and oil filled transformer.
- ANSI/IEEE standard. C57.19.00 is used to explain performance characteristics, test procedure for outdoor power apparatus bushings [16]. It is used to explain different tests of bushings, service conditions, electrical and mechanical requirements,

dimensions and design requirements and ratings of outdoor bushings. It explains definitions of different phenomena in bushings. This standard is most widely used in European countries.

- IEEE standards C57.19.100 give information about the application of power apparatus bushing, thermal loading above nameplate rating for bushings used in power transformers, circuit breakers and bushings connected to isolated phase bus, it gives guide line for the application of bushing at high altitude, during maintenance work and in contaminated environment [17].
- IEC Publication 137 is used for bushings operating at alternating voltages above 1000 V. It is used in European and Asian countries [18].

2.3 Other bushing design parameters

The principle elements in construction of an oil filled capacitance graded bushing are conductors, top and lower insulators, the mounting flange, the oil level gauge, oil expansion cap, clamping setup. The bushing components are shown in figure below and design parameters are discussed.

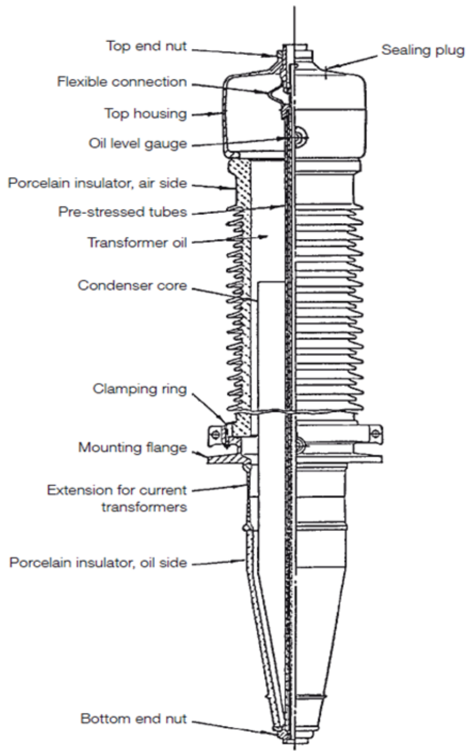

Figure 2.6 Bushing components [19]

2.3.1 Conductor size and material

Conductor size is dependent on the current rating. For higher current ratings conductor with larger diameter is required. Conductor size and material is also dependent on two factors. First is the skin depth and second is the power losses generated in conductor because of current flow. At 60 Hz the skin depth of copper is 1.3 cm and skin depth of aluminium is 1.6 cm.

Most of the current flow in outer region of conductor and also towards the inwards until the skin depth of material is reached. The power losses equation is given below.

$$P_{losses} = I^2 \times R = I^2 \times L \times \frac{\rho}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.3$$

I=current rating

L=Length of conductor

A is the area of conductor

ρ is the resistivity of conductor material and selection of material is also dependent on it.

From equation 2.3 it is clear that power losses in conductor are dependent on the diameter of the conductor and inversely proportional to the diameter of the conductor. Different diameter values are given in IEEE/ANSI standards according to different current ratings so conductor diameter is selected from these standards. Most companies in world follow these standards during conductor diameter selection. The conductors with larger diameter will have higher withstand voltage and partial discharge inception voltage. The conductor with larger diameter can withstand large forces in conductor so it is mechanically beneficial to have larger diameter. Temperature is also very important factor in selection of conductor diameter. Temperature values are given in IEEE/ANSI standards [9].

2.3.2 Insulators

The size or length of insulator is dependent on the insulating media and construction method of the bushing. The length of insulator must be such that it can withstand both transient and steady state voltages in the bushing. If there are two different insulation media on either side of the bushing then the length of insulator is determined by the insulation with lower dielectric characteristics [9].

2.3.2.1 Air insulators

The length of insulator used in air at atmospheric pressure is dependent on the lightning impulse voltage under dry conditions, power frequency and switching impulse voltages under wet conditions. These measurements are made at standard atmospheric pressure and 20 °C temperatures. When bushings are used at higher altitudes the length of insulator in interface with air is increased to overcome the lower breakdown strength of air at higher altitudes. Insulation length is shorter for condenser bushings [9].

2.3.2.2 Oil insulators

Mineral oil has higher dielectric strength than the air so length of insulator exposed to oil has less length as compared to air exposed insulator. No sheds are used for oil exposed insulators.

2.3.2.3 SF6 gas insulators

Length of SF6 gas insulators is almost equal to oil immersed insulators. No sheds are required in SF6 gas insulators.SF6 gas must be free from particles because particles can affect the dielectric strength of SF6 gas [9].

2.3.3 Metal flange

Metal flange is used for two purposes. The first is to mount the bushing on the apparatus for which it is used and the second is to contain or hold the gasket. Metal flange is made of cast aluminium in case where bushing is used a lot whereas in case of low activity apparatus it is made up of aluminium plates or steel. In case of high current bushing, nonmagnetic material or aluminium is used in flange to avoid magnetic losses [9].

2.3.4 Oil reservoir

Oil Reservoir is very important for a bushing because it is used to control the oil level in the bushing. It is also called expansion cap. It is necessary part of large bushings. The main reason for using it is to control the oil level inside the bushing because mineral oil expands and contracts with temperature. During oil expansion with increasing temperature the extra oil is stored in the oil reservoir. In case of oil impregnated paper bushing the impregnated papers must be immersed in oil in order to increase the dielectric strength of the material so an oil reservoir is used to ensure that the oil level is above the papers at a lowest possible temperature. The oil reservoir must also have gas like nitrogen to ensure that excessive pressure is not created at high temperature in bushing. Excessive pressure can result in oil leakage. The oil reservoir can be mounted on top of large bushings. Horizontally mounted oil filled bushings have oil reservoir mounted on the metal flange with some bellows either inside or outside in order to overcome the expansion and contraction respectively with oil temperature. An oil level gauge is used in the oil reservoir to check the oil level in the bushings. There are two types of oil gauges. First is the clear glass type oil gauge which is made from clear glass so that the oil level is observed from any side around the bushing. The second type is the two piece gauge in which one piece is inside the reservoir attached to magnet which is rotating on axis perpendicular to reservoir wall and the piece outside the oil reservoir is a gauge dial which is also attached to magnet but this magnet follows the rotation of magnet inside the oil reservoir but this type has one disadvantage that the oil level can only be observed at an angle of the 120° [9].

2.3.5 Clamping system

The clamping system provides mechanical support to the bushing. There are three types of clamping system. Two types are commonly used in the bushing and the third type is less frequently used. The first type is mechanically clamped type which uses an external flange on the ends of insulator and bolts are used to fasten these flange. A grading ring is used to shield the bolts from electric fields. It is economical and compact. This type has a stress at clamp bolts that can result in breakage. The second type is a centre clamped type in which the springs are used in reservoirs located at the top of bushing. When the spring is released the central conductor is in tension that results in simultaneous compression of insulators, flange, gasket and terminal at the end of insulators. This compression results in sealing of gasket. This type is also economical and compact but it has chances of oil leakage due to cantilever or seismic forces on insulator. This type is used in capacitive graded bushing. The third type is cemented type. In this type metal flange is around the end of bushings. The gap between metal flange and insulation is filled with such material that can prevent load concentration on porcelain. It is used in pressurized gas bushings [9].

2.3.6 Temperature limits

Bushing parameters like oil viscosity, partial discharges in bushing etc. are temperature dependent depending on the construction type and the material used in bushing. In solid type bushing central conductor is used along with porcelain or epoxy resin and the sealing gaskets. The bushings have maximum allowable temperature of insulators or sealing gaskets.

OIP insulation which is used to provide electrical and mechanical support in condenser bushing has temperature limitation of 105 $^{\circ}$C. Maximum temperature limitations for these bushings are given in standards [20].

Ambient air temperature = 40 $^{\circ}$C

Immersed oil temperature= 95 $^{\circ}$C average taken for 24 hours period and the maximum increase is 105 $^{\circ}$C in any hour.

Maximum hottest spot temperature=105 $^{\circ}$C

2.4 Maintenance of bushing

When bushing is installed on equipment without any damage or breakage, it will continue to operate with apparatus unless there is a thermal, mechanical and electrical overload. There are also chances of flaws in design of bushing or there are chances of incipient damage during shipment or installation. Therefore a bushing needs regular inspection. There are different things to be monitored regarding bushings.

Figure 2.7 Maintenance of bushings [21]

2.4.1 Oil level

Oil level must be checked periodically because if the oil level is low it means that there is some leakage in the bushing. Leakage can be through gasket, soldered seal or there is a possibility of insulation breakdown. Leakage on the air side can result in entrance of water in bushing that deteriorates the dielectric integrity along the inside of the insulator.

In a capacitive graded bushing the core must be covered with oil. If the oil level drops below the top of core it results in unimpregnation of paper. The dielectric property of the insulation deteriorates and there is a possibility of insulation failure [9].

2.4.2 Power factor and capacitive measurements

This test can be performed in two ways

2.4.2.1 Ground specimen test

In this test currents, capacitance and powers of all leakage paths are measured between the central conductor and all grounded parts of bushing. Measurements are performed in internal core insulation, oil and leakage path along the insulation surface. By using a guard circuit the leakage path can be minimized [9].

2.4.2.2 Ungrounded specimen test

In this method all measurements are performed between the central conductor and voltage taps that are ungrounded. The main advantage of using this method is the minimization of leakage path along the insulation surface and separate tests are possible when bushing is mounted on apparatus as well.

It is suggested to perform power factor and capacitive measurements at a time of installation, after a year of installation and after every 3 to 5 years. Increase in power factor is an indication of deterioration of insulating system. Increase in power factor can result from dirt on the air end of insulator or wet condition on air end of insulator and excessive leakage current flowing along the insulation of the bushing.

Increase in power factor from conductor to tap indicates the deterioration inside the core. Increase in power factor from tap to flange indicates the deterioration of oil. If the power factor is doubled as compared to normal value at installation then it is monitored at regular intervals and if the value is tripled the bushing should be removed from the apparatus.

Bushing capacitance is also very important in analyzing the condition of the bushing. If the change is 2 to 5 percent then it means that insulation between grading elements has deteriorated so bushing should be removed from an apparatus as early as possible [9].

2.4.3 Damage of air end insulators

There are chances of damage in porcelain part of bushing during shipment, installation or from the flying part of other equipment in substations during explosives. Sheds are made up of porcelain. Chips can be broken out from sheds. These can be repaired by grinding the damage parts, filling the created voids and painting over the damage part with paint. Sometimes the damage extends to core of bushing. The damaged portion must be closely monitored in order to avoid oil leakage.

Bushings must be washed regularly after a certain period of time in polluted environment. Washing can be done by de energizing the bushing and washing by hand using cleaning agents [9].

2.4.4 Dissolved gas in oil analysis

It is not good to perform dissolved gas in oil analysis on routine basis because the bushing has a limited amount of oil therefore if the analysis is performed many times it will decrease the oil level in bushing. In this analysis CO and CO_2 gases indicate that the paper in bushing is deteriorated. It is only performed if the power factor/capacitance measurements values are high, which indicates there is something wrong in the insulation [9].

3 The phenomenon of partial discharge (PD)

Partial discharges are basically localized electrical discharges happening in the insulation. Discharges occur inside a voids or cavities in liquid or solid dielectrics. Initially partial discharge was termed as "Glow". In 1950 era terms like glow measurement and glow inception voltage were used. The term PD is used by IEC which is now universally accepted. PDs results from gas discharges in the form of a partial breakdown phenomenon in gaseous or liquid regions of the insulation [4].

3.1 Types of partial discharge

There are two types of partial discharges [4].

3.1.1 External partial discharge

PD occurring on the surface of a solid insulating material and in gases around electrodes is called external partial discharge. Corona discharge is an example of external partial discharge. In case of external partial discharge high frequency electromagnetic disturbances, corona losses and chemical effects are more dangerous as compared to possible damage caused by the PD to insulation. This type of discharge occurs from sharp edges or boundaries [4].

3.1.2 Internal partial discharge

PD occurring as gas discharge surrounded by solid or liquid insulating material is called internal partial discharge. Internal partial discharge occurs in voids or cavities filled with gas inside the solid and liquid insulating material. These surface voids are generated from partial detachment of insulation from metallic surface or the gap between two insulating materials. It also occurs from the edges of metallic surface. If the electrode or any conducting material is placed inside the solid or liquid in such a way that it enhances the local field, then it results in local partial discharge and in the end destruction of insulating material. These electrodes also cause gliding discharges. Internal partial discharge accelerates the ageing process. The healthy part of insulating material is also affected by the partial discharge and the acceleration of ageing of insulating material results in failure much earlier than the expected life [4].

3.2 Different terminologies in partial discharge

3.2.1 Electrical discharge

Electron avalanche results in movement of electrical charge through insulation medium which is called electrical discharge [22].

3.2.2 Partial discharge

It is a type of Electrical discharge but it partially bridges the insulating medium between two conductors. Corona discharge, surface discharge and internal discharges are types of partial discharge. Incomplete breakdown is also called partial discharge.

3.2.3 Surface discharge

Surface discharge is a partial discharge occurring on the surface of solid insulation not covered by conductor or discharges occurring from conductors in gas or liquid insulation medium.

3.2.4 Corona discharge

It is basically an external partial discharge it occurs in gas or liquid insulation around the conductors. It is not inside the solid insulations. In uniform fields, ionizations leads to complete breakdown where as in non-uniform fields acoustic and luminous discharges are observed before the complete breakdown take place and these discharges are called coronas [23]. Corona also occurs from the sharp edges of electrodes.

3.2.5 Discharge inception voltage

"The minimum voltage level to establish initial discharge is called inception voltage" [10].

3.2.6 Discharge extinction voltage

"The minimum voltage to maintain a discharge once it has been established is called extinction voltage" [10].

3.3 Signature of partial discharge in electrical insulating materials

The development of electrical apparatus with increasing power density results in increased electric stress on insulating materials. Therefore the phenomenon that limits the electric strength of insulating material must be understood for economic and safety reasons. The insulations are manufactured industrially. There are irregularities on surface or in the volume of insulation inspite of all quality control and continuous improvement in production methods. The voids in solid insulating materials results in a local field disturbance which is the starting point for the destruction of material by partial discharge.

The partial discharges have repetitive characteristics and they attack the dielectric material pointedly. Although individual discharges have low energy content but they damage the insulating material because of local concentration and repetitive characteristics. Partial discharge results in change of properties of material. It results in accelerated ageing of insulation material. During the design phase of insulation, the partial discharge phenomena consideration is also very important besides thermal, mechanical and dielectric properties study of insulation.

Partial discharge has negative effect on insulating material. During design phase of power apparatus it is important to consider that no defects are created in insulation, it means to avoid the cause of PDs. They can develop for short time in insulation during overvoltage. These short duration PDs also damage the insulation but this damage is long term. The capacity of material must be such that it can sustain these short duration PDs for long period of time. The evaluation of damages caused by PDs regarding life of insulation system is very important.

The relation between partial discharges measured parameters and damage in insulation must be known [24].

3.3.1 Gaseous insulating materials

Air is very important insulating material. It is used as insulating material since the beginning of high voltage technology. SF6 is also very important insulating material. SF6 is used for medium voltage and high voltage ranges because of its superior dielectric properties as compared to air. SF6 is used for indoor application. SF6 insulation is used in switch gear applications.

In outdoor application air is available in large amount therefore large gaseous insulating medium is available but in indoor apparatus e.g. SF6 insulated switchgear or cable systems, a limited amount of SF6 is available. Because of effectively infinite volume of air the PDs do not damage the insulating medium but in indoor systems it affects the components of power system [24].

The external partial discharge is most common in outdoor applications, occurs at metallic sharp point or edges by local field enhancement at these points. Inhomogeneous field accelerates the electrons in front of these sharp points or edges. These electrons collide in elastically with gas molecules resulting in energy transfer. Thereafter dissociation, ionization and excitation of gas molecules take place. If humidity is present at discharge location then it results in formation of acid products which is very dangerous. In case of SF6 insulated systems reaction products like SF_2, S_2F_2 and SF_4 are formed and in the presence of humidity hydrofluoric acid is formed [24].

The formation of gases has direct effect on insulation system. PDs also result in continuous formation of charge carriers which later on build a charge cloud around the inhomogeneous field. This space charge cloud can be called screen. During switching action overvoltage pulses are developed and this screen in comparison to PD free setup provides large electron concentration initially. The electrons having high energy start an electron avalanche which is accumulative process and it can lead to electrical breakdown of insulation system [24].

3.3.2 Liquid insulating materials

Liquid insulating materials are very important. They are used in closed containers and besides providing insulation to equipment from high voltage they also serve the purpose of cooling the winding and core and extinguishing the arc in circuit breakers. Mineral oil is most important liquid insulating medium. The properties of insulating materials are not only dependent on the material itself, it also depends on foreign contents added into it. Cellulose fibers, dissolved gases, water contents and metallic dust particles are very important in determining the insulating properties of liquid materials especially mineral oil. The inhomogeneity is already present in insulating material and these water contents, cellulose fibers and metallic dust particles can initiate the partial discharge. These partial discharges results in carbonization of oil during local heating and the formation of waxes and acids in oil which accelerates the ageing of insulation material by increasing the loss factor. The insulation strength is decreased by dissolved gases and bubbles developed at edges. Such large voids distort the field distribution and are a starting point of discharge activities [24].

Liquid insulations [24] contain voids and those voids are filled with gases of lower dielectric constant as compared to liquid insulation so the electric field strength of the void is higher than liquid insulation therefore there is a chance of electric field breakdown of void at normal operating voltages.

The phenomenon of gas absorption or generation is called gassing. In gas absorption liquid PDs will disappear whereas in gas generation liquid more PDs will produce until the insulation breakdown. The gassing tendency of a liquid depends not only on the nature of liquid but it also depends on many experimental parameters e-g applied voltage, applied voltage duration, temperature, geometry of test setup etc. [25]. Once the partial discharge is initiated it generates the gas bubbles and these gas bubbles also create PDs.

3.3.3 Solid insulating materials

Solid Insulating materials are very important for any insulation system as they provide mechanical support to electrodes and also keep them away from high electric potential. Solid insulations are used in all kind of electrical power apparatus. These insulations have higher breakdown value as compared to oil and gases. Both inorganic and organic materials are used as solid insulating material.

Solid insulating material can be divided into two categories regarding partial discharge. Mica, porcelain and to some extent glass are considered as PD resistant. Their dielectric properties are not damaged even with long term PD stress. These materials have excellent temperature resistant property. Organic polymer materials like polyethylene, cross linked polyethylene, polytetrafluoroethylene (PTFE) and cast resins etc. are considered as PD sensitive. Long term PD exposure leads to complete breakdown in these materials. The physical interrelationship between PD deterioration and polymeric material is not still clearly understood [24].

There are two types of partial discharge occurrences in solid insulating material.

3.3.3.1 Surface discharges

Inhomogeneous field distribution is not avoidable near the metallic portion of insulation systems. These metallic fixtures are most common location for surface discharges. There is also tangential electric stressing on insulation material. The concentration of partial discharges in one specific region results in local carbonization of that specific region especially in case of organic plastic material. The local carbonization decrease the creepage distance. The electrical stress perpendicular to surface also results in acceleration of insulation degradation. This degradation of polymer material by partial discharges is observed with help of infra-red spectroscopy. During carbonization carbon radicals are formed which results in per oxide radicals after reaction with oxygen. The radicals are formed as a result of polymer chain breakage which causes irreversible oxidation of insulating material. Crystals of oxalic acid are formed on the surface of polyethylene insulating material as a result of reaction with air. If the materials are stressed tangentially for long time it results in formation of sharp peaks of crystals which increase PD concentration and finally leads to complete breakdown.

Polymer materials are sensitive to partial discharge because charge carriers enter the insulating material and they are captured by inhomogeneities within the molecules and crystalline structure. The examples of these in homogeneities are branches, terminal points of chain molecules crystalline boundaries and boundary layers. When charge carriers enter the material it results in local electric field variation. The local electric stress is developed without any change in load stress. The temperature is also very important parameter for evaluation of PD sensitivity [24].

This discharge is along the surface of dielectric. After discharge the electric field is changed and the healthy portion of insulation is also affected by discharge, as discharge is extended into that region also. The size of discharge is unequal in opposite polarities when an alternating voltage is applied. There are small discharges for negative electrode and large discharges for positive electrode because of mobilities of positive and negative charges. Leakage current through the conducting film on insulation surface e-g aluminium foil on paper is also a source of surface discharge. The electromechanical stress is the main problem for organic insulation. Mechanical stress increases the destruction process of organic insulation so when polymer materials are tested regarding surface discharge resistant property the mechanical stress and surface discharge is applied simultaneously. Organic materials have short life when surface discharge is present. Surface discharge is observable from light emission or it can be detected by voltage pulse. In voltage pulse technique it gives asymmetric pulse pattern. If the applied voltage is increased the pulse height increases so surface discharge increases with increasing applied voltage [10, 24].

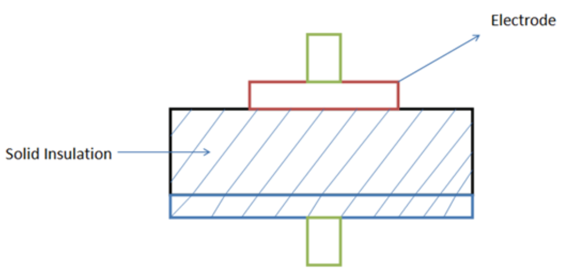

Figure 3.1 Surface discharges occurring on surface of insulation

3.3.3.2 Internal discharges

Electric field in air filled cavities is higher than the electric field of material because of difference in their dielectric constants and also the shape of cavity is very important. In solid insulating material cavities are of irregular shape. These cavities can be left in manufacturing phase. Cavity in solid insulations can be breakdown by the presence of metallic particles, presence of charge on cavity and semi conducting deposits on surface cavity.

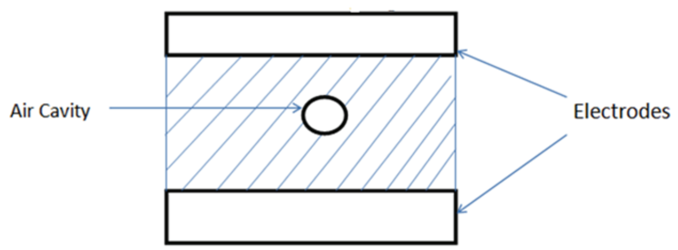

Figure 3.2 An air filled cavity in solid insulation

The cavities filled with air can breakdown at atmospheric pressure. It occurs at normal operating voltage because of this breakdown the charges on cavity transfer to opposite side surface but few charges are left on surface of cavity as the surface resistivity is higher. These remaining charges change the electric field of cavity and the next discharge take place at different location of cavity. When alternating voltage is applied the discharge of opposite polarities are produced alternatively. There are charge clusters of opposite polarities at different sites of cavity that results in discharge along cavity surface inside the insulating material. A conducting channel is formed between the electrodes that bridge the cavity. It results in insufficient voltage for breakdown of gas and in the end discharge extinguishes. The extinction voltage is less than the inception voltage because after the initial discharge lower voltage is required to maintain the discharge, it can be 25 % lower in many cases. If cavities are small (< 0.15 mm) and filled with air at atmospheric pressure, discharges are not detected by pulse discharge detectors. These discharges are called pseudo glow discharges. The cavities or voids of such small dimensions are not dangerous for solid insulations [10, 24].

3.3.4 Mixed dielectrics

Mixed dielectric insulations have great importance in technical insulation. Commonly used mixed dielectrics are solid liquid combination, liquid impregnated thin sheets of paper or plastic. Nowadays it is common to have composite insulation system for power apparatus. These insulation systems have different dielectric materials either in parallel or series with each other. It is possible to obtain superior dielectric properties by using combination of different dielectrics as compared to single dielectrics. Liquid insulation fills the cavities in solid insulation and its high insulation strength avoids the occurrence of partial discharges. There are few examples given below [24].

- Oil paper insulation in high voltage cables
- Foil capacitors impregnated with liquid hydrocarbons
- Epoxy resins with inorganic filler materials
- SF6- impregnated foil insulation in measuring transformers
- Oil Impregnated paper Bushings

In mixed insulations the sources of PDs are different from the single insulations. Liquid /solid insulation is common in industry e.g. oil impregnated papers. In this case dielectric constant difference between insulating materials is less. The dielectric strength of oil is 30 times greater than the air so discharges production cannot take place at normal operating voltage or condition. Breakdown voltage must be high as compared to air.

In oil impregnated papers insulations discharge can take place from gas bubbles in the oil or from the severe non uniformity of solid insulation surface. The switching surges can also produce the partial discharge. The discharges are also created by breaking of the molecular bonds in oil. This gas can produce bubbles that results in more discharges and again gas is produced from these discharges. This recurring process leads to unstable situation. In an oil impregnated system the particles present can easily move because of movement of oil so these particles move to high field regions by dielectrophoretic forces. So the part of insulation that is unaffected can start discharge later. The sharp edges of solid part of insulation system can also cause discharges [10].

The main advantage of mixed dielectric is that it restricts the PDs to only one portion of insulation. So it avoids the characteristic disadvantage of single insulation system. There are chances of damages in mixed dielectric also. Weak spots can be formed in mixed insulation at boundary layers. There are chances of PD ignition from these boundary layers because the voids can be created at boundaries. In oil paper insulations the gaseous products formed in oil and solid products developed at paper insulation have important role in PDs ignition. The carbonization of paper and formation of products on paper surface increases the conductivity of paper. When the conductivity of solid insulation is increased the effective insulation path is reduced. When cellulose fibers of paper absorb moisture they wander in inhomogeneous electric field and they decrease the electric field strength of insulating material by forming cellulose bridge [24].

Careful impregnation is very important for oil impregnated papers and foil capacitors impregnated with hydrocarbons because if these solid insulation are not wet with respective liquid insulation it results in formation of gas filled voids so even with low electric field stress PDs are ignited which results in complete breakdown of the insulation system as it damages the solid insulation completely.

Epoxy resins are filled with inorganic materials in order to provide thermal and mechanical strength where it is demanded. Quartz and metallic oxides can be used as inorganic materials. It also increases the long term electric strength but these inorganic materials are source of PDs in insulation system. Once the PDs are generated from these inorganic materials it results in complete breakdown of insulation system. Epoxy resin mixed with mica is another example of solid insulation mixed with solid insulation. As compared to pure epoxy resin the life of the insulation system is increased by one order of magnitude. Damages are restricted due to inclusion of mica because mica is PD resistant material but there are chances of formation of voids at the boundary due to dissolution of resin mica boundary [24].

Inorganic materials are PD resistant so these are better as compared to organic materials regarding electrical strength but in all kind of suspension insulators and bushings high mechanical strength is required along with high electrical strength so ceramic inorganic materials like porcelain, mica etc. are replaced by fiber reinforced plastic materials as described earlier [24].

3.3.4.1 Ageing and breakdown due to partial discharge

During manufacturing process the gas filled cavities are created within the mix dielectric or adjacent to the interface between insulation and conductor. When a voltage is applied to such insulation the discharges occur in gas filled cavities. It results in transfer of charge between two points. The charge transfer is the cause of discharge of cavity capacitance. The deterioration is produced in insulation from this charge on dielectric surface. The charge transfer results in forming a dipole moment and the field in cavity opposes the applied electric field, therefore the discharge extinguishes. The degree of ageing depends on inception voltage and discharge magnitude. Inception voltage is dependent on thickness of cavity and the permittivity of insulation. The electric field stress in cavity filled with gas is given by [22].

$$E_{cavity} = \varepsilon_r \times E \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

Where E is the electric field strength of insulation, ε_r is relative permittivity of insulation and E_{cavity} is electric stress in cavity and it will be more than the breakdown strength of gas in cavity.

For breakdown of gas in cavity the discharge has to start at one end and progress to other end. The charge accumulates on cavity surface so the voltage drops and the discharge extinguishes. The discharge extinguish voltage is lower than the inception voltage [22].

Discharge phenomena in small cavities can be modeled by using Townsend's discharge mechanism. According to this theory breakdown voltage is a function of pressure applied on cavity and size of the cavity [22].

$$U_b = F(p \times d) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

This expression is also called Paschen's law. From the expression 3.2 and 3.3 it is possible to calculate the breakdown voltage and maximum permissible electric field strength of insulating material in order to avoid the partial discharge [3].

3.4 Electrode configuration with partial discharges

3.4.1 Cavity in insulation

In solid insulations gas filled cavities are main source of internal partial discharge.

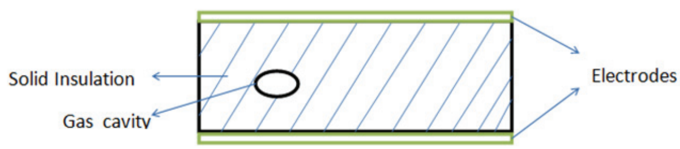

Figure 3.3 Cavity in solid insulation

3.4.2 Surface voids in insulation

Surface voids are formed by partial detachment of insulation from electrode. These surface voids are source of internal partial discharge.

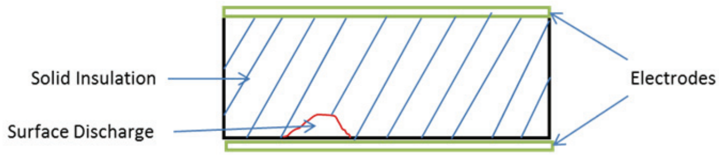

Figure 3.4 Surface voids in insulation

3.4.3 Gap in insulation

The gap inside the insulation or between electrode and solid insulation is a source of internal discharge.

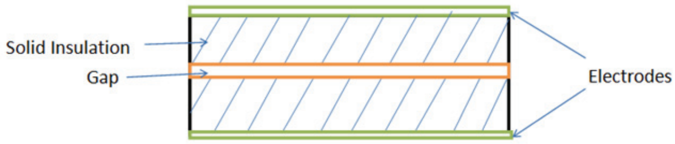

Figure 3.5 Gap inside the insulation

3.4.4 Edges of electrodes

Edges of electrodes are source of partial discharge. Partial discharge occurring from these edges that are parallel to insulation surface is called gliding discharges. Corona can also occur from these sharp edges [4].

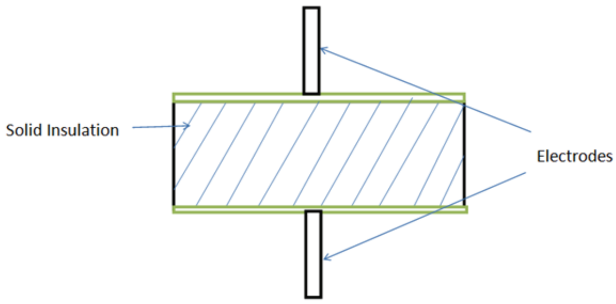

Figure 3.6 Edges of electrodes

3.4.5 Electrodes perpendicular to insulation or inside the insulation

When electrode is perpendicular to insulation and inside the insulation the edges of electrode create severe local electric field buildup which results in local partial discharges which destroys the solid insulation. It is the same in oil immersed insulations.

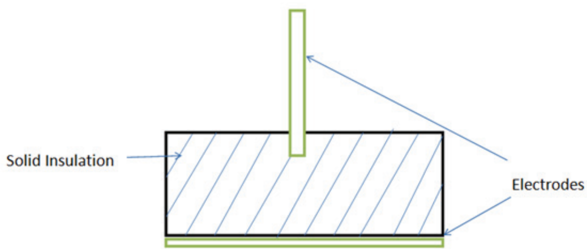

Figure 3.7 Electrode configurations inside the insulation

3.4.6 Corona occurrence from sharp points

In this setup one electrode is in rod form and other is in plane configuration. Plane electrode is earthed and rod electrode is at higher potential. When rod electrode is brought near to plane electrode the external partial discharge occurs from sharp edges of rod which is shown in figure as small lines. It is also called corona [4].

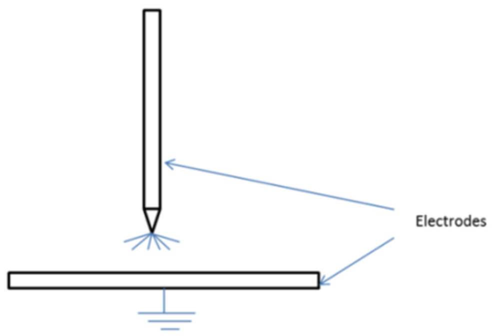

Figure 3.8 Corona occurrence

3.5 Pattern of partial discharge caused by various defects

Partial discharge in solid and liquid insulations must be considered as dangerous and the degree of danger depends on type of material used for insulation. It is difficult task to point out the area of occurrence of PDs. But from the PD pattern appearances one can conclude the site of occurrence in insulation as the pattern appearance is dependent on the location and type of defects, so improvements can be made in manufacturing process. In PD patterns alternating voltage is superimposed with PD pulses. The time dependent patterns are shown on an oscilloscope [4].

3.5.1 PD pattern of Corona in gas insulating materials

It occurs at the tip of sharp points as high voltage potential. PD pulse occurs at the peak negative half cycle of alternating voltage and with a small increase in voltage above the onset value it develops into a uniform row of PD pulses and these are symmetrical about the maximum voltage. With increase in voltage the number of pulses increases but the amplitude remains same. PD pulses occur in positive half cycle at higher applied voltage [4].

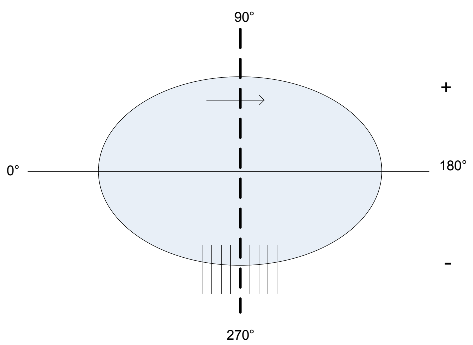

Figure 3.9 PD pattern for corona in gas insulation

3.5.2 PD pattern of corona in liquid insulating materials

It occurs when a sharp point is immersed in liquid insulation. During this type, the discharges occur simultaneously in both half cycles. In this case large pulses occur in positive half cycle and small pulses occur in negative half cycle. Pulses increases with increase in voltage but the amplitude remains same [4].

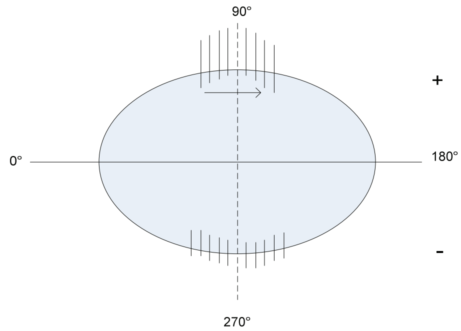

Figure 3.10 PD pattern for corona in liquid insulation

3.5.3 PD pattern of voids in solid insulating materials

In case of gas filled voids in solid insulations, PD pulses occur between zero crossings and peaks of both half cycles. Within the polarity pulses have different amplitude of charges. On an average the amplitude of pulses is same in both half cycles. They extinguish on reaching the peak of polarity. This type of discharge is dangerous to insulation [4].

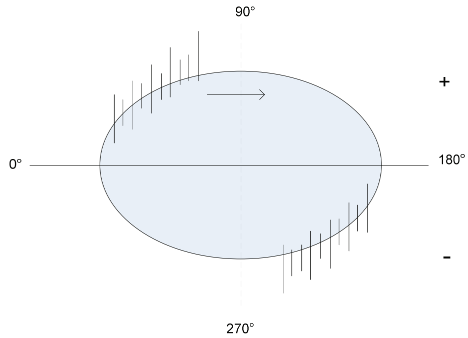

Figure 3.11 PD pattern for voids in solid insulation

3.5.4 PD pattern of gas bubbles in liquid insulating materials

The discharge pattern is same as that of gas filled voids in solid insulations. On average the amplitude is same in both polarities and discharge extinguish on reaching the peak. This type of discharge is dangerous to insulation [4].

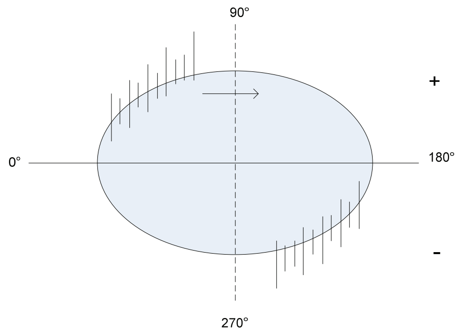

Figure 3.12 PD pattern for gas bubbles in liquid insulation

3.5.5 PD pattern of partial breakdown between two metallic grading screens in a capacitive graded bushing

Discharges have the same pattern as gas bubbles in liquid materials and voids in solid insulations have. It is dangerous for capacitive grading of insulation [4].

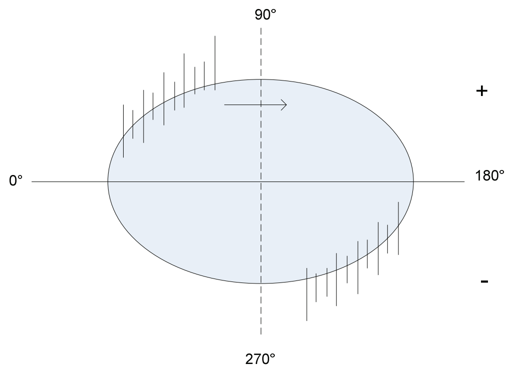

Figure 3.13 PD pattern between two metallic foils

3.5.6 PD pattern of voids in solid insulating materials at electrodes and surface discharge at electrodes

In this case a PD pulses occur between zero crossing and peaks of both half cycles but on average amplitude is larger in one half cycle. If the gas filled cavity is directly next to high voltage electrodes, the discharge occurs on high voltage side and the pattern is larger in positive half cycle. In case of cavity next to earthed electrode the discharge occurs in low voltage side and the pattern is larger in negative half cycle because the flow of charge is towards one side of voids. It is basically gliding discharge [4]

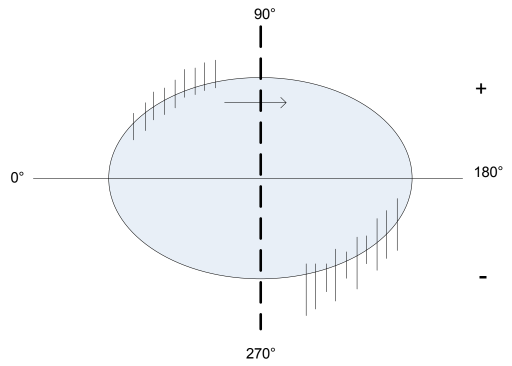

Figure 3.14 PD pattern from cavities next to electrodes

3.5.7 PD pattern of poor contact between metallic parts

When there is poor contact between metallic parts, discharges occur in both polarities. The PD pulses are symmetrical about the zero crossing in both half cycles [4].

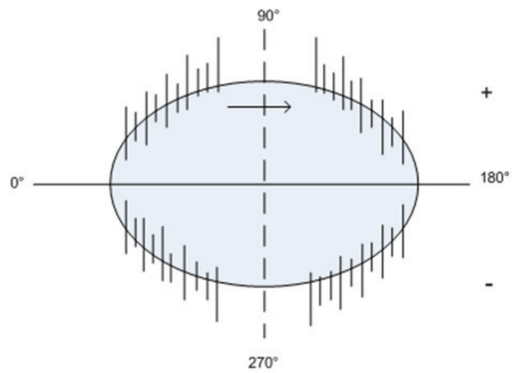

Figure 3.15 PD pattern from poor contact between metallic parts

3.6 Equivalent circuit of discharge pattern inside cavity

The equivalent circuit used to represent the discharge in cavity when alternating voltage is applied is shown in figure below 3.16. In this circuit C_c represents cavity capacitance,C_b represents capacitance in solid insulation area in series with cavity and C_a represents capacitance of remaining solid insulation.

When there is a discharge in cavity the spark gap that is parallel to cavity also becomes conducting. After discharge the voltage across the cavity decreases but if the applied alternating voltage is increasing, superposition of electric field produced by charge transfer from cavity and the main field increases the voltage across the cavity to V_c. When voltage across cavity reaches the breakdown value of gas filled cavity, discharge takes place again.

There is a residual voltage across the cavity after the discharge. This residual voltage limits the discharges per cycle. If there is no residual voltage across cavity then the discharges almost double. As the applied voltage increases discharges increases. The discharges occur at inception voltage. After discharge voltage across cavity becomes zero but it has repeating characteristics during one cycle of applied voltage until the applied voltage is higher than the inception voltage either in positive polarity or negative polarity. The discharge pattern is not regular because of charge left on cavity and many discharge sites on same cavity. As the applied voltage is alternating so there are positive and negative half cycle discharge patterns [10].

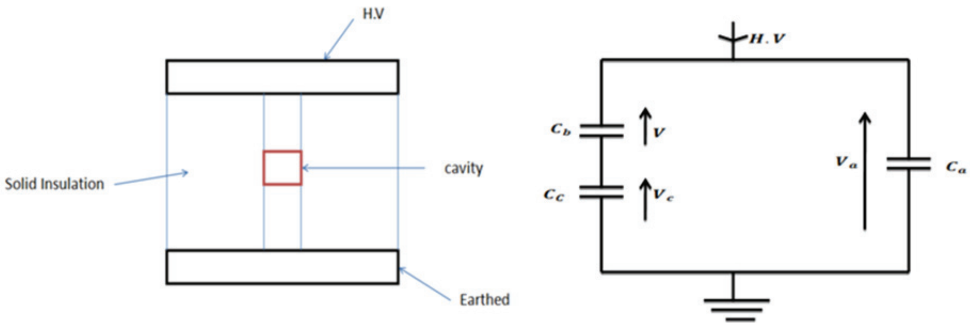

Figure 3.16 Equivalent circuit diagram of cavity in solid insulation [10]

3.6.1 Calculation of energy in a discharge created by cavity

The equivalent circuit of Fig 3.16 is considered. The total capacitance of dielectric system is given by [10].

$$C = C_a + \frac{C_b \times C_c}{C_b + C_c} \quad \ldots\ldots 3.3$$

$$\Delta V_a = \Delta V_c \times \frac{C_b}{C_a + C_b} \quad \ldots\ldots 3.4$$

$$q_a = \frac{C_b \times C_a}{C_b + C_a} \times \Delta V_c \quad \ldots\ldots 3.5$$

$$C_b \ll C_c \ll C_a \quad \ldots\ldots 3.6$$

$$q_a = C_b \times \Delta V_c \quad \ldots\ldots 3.7$$

The energy in a discharge is calculated by taking difference of energy before and after the discharge in capacitance of cavity.

$$w = \frac{1}{2} \times C_c \times (u^2 - v^2) \quad \ldots\ldots 3.8$$

$$(u^2 - v^2) = (u - v) \times (u + v) \quad \ldots\ldots 3.9$$

If there is some residual voltage in cavity then voltage across cavity is given by

$$\Delta V_c = u - v \quad \ldots\ldots 3.10$$

If residual voltage is not considered and by putting equation 3.9 and 3.10 in 3.8, the following equation is obtained.

$$w = \frac{1}{2} \times C_c \times \Delta V_c \times u \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.11$$

When there is no discharge in voids and discharge take place at peak voltage, breakdown voltage u is given by

$$u = \frac{C_b}{C_b + C_c} \times V_{peak} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

Put equation 3.12 in 3.11

$$w = \frac{1}{2} \times C_c \times \Delta V_c \times \frac{C_b}{C_b + C_c} \times V_{peak} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.13$$

$$C_b \ll C_c$$

As cavity depth is less than insulation thickness

$$w = \frac{1}{2} \times C_b \times \Delta V_c \times V_{peak} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.14$$

From equation 3.7

$$w = \frac{1}{2} \times q_a \times V_{peak} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.15$$

3.7 Non-electrical PD characteristics parameters

The partial discharge phenomenon in insulating material is also observed from non-electrical parameters. The PDs not only results in high frequency transients and currents it also results in a chemical, an acoustic and an optical affects. The external or surface discharge is observed from acoustic and optical methods.

Traditionally hissing test was used to detect the external discharge. The electrical insulation was rejected if the hissing sounds were listened from the equipment on the application of high voltage. This method is not good because the human ear sensitivity is low in noisy conditions. In a good environment human ear can detect the discharge of 40 pC. By using a stethoscope detection of a 10 pC is possible in good conditions. Most of the acoustic energy lies in the ultrasonic range. The ultrasonic techniques are better than an audio frequencies range. In order to observe the acoustic effects of partial discharge directional microphones with amplifiers in sonic and ultrasonic range are required. A 40 kHz microphone with amplifier and meter is required to display the level of ultrasound from discharge. Discharge of 5 pC can be detected from this setup. By using a parabolic reflector with this setup it is possible to obtain directional detection therefore a location of discharge can be obtained but the disadvantage of ultrasound measurement is its variable attenuation [10].

The light emission detection is considered as optical method for discharge detection. The light emission can be used to detect the location of discharge but it is helpful only in case of location of large discharge sources e.g. large cavities detection and it is also not possible to detect internal partial discharges. The local heating from these emissions can be used as detection of location but it requires placing thermocouples inside the insulation to locate hot spots which is not possible in many insulation e.g. bushings so it is not practical.

In order to observe the chemical affects, a long duration is required and totally enclosed surrounding is required. It is possible to observe the chemical affects in SF6 insulated switch gears or inside the oil tank of transformer. In oil insulated equipment the dissolved gas analysis is used to detect the discharges in oil. The ozone level in air filled cavity is used to detect the discharges. The chemical analysis of an insulation material detects discharge but it takes time. The X ray micro-probe technique and infra-red technique is used to detect the discharges in organic materials. It can be used in the oil impregnated paper insulation to detect the wax on papers. In these techniques, the insulation needs to be dissected so it is not practical to perform these tests as routine tests [10].

The electrical methods for determining partial discharge in insulating materials are highly developed regarding the reproducibility and a comparability of experiments or testing. Even in an acoustic method the voltage is measurable at the end of coils of microphone to determine the partial discharge [4].

3.8 Partial discharge resulting from electrical trees

The inhomogeneity and electrodes with small radius of curvature are avoided during the manufacture of solid insulation. In the case of polymeric materials these defects results in severely electrical stress which leads to a starting point for electrical trees. The starting mechanism of an electrical tree is still not clear. If there are gas filled voids in solid insulating materials then the electrical tree is initiated by the erosion of walls of these voids. But if there are no voids then breakthrough of solid insulation is not clear. There is hypothesis that electro physical stressing of boundary layers results in breakthrough. After breakthrough the PDs are generated. The partial discharge is a repetitive phenomenon so a chemical degradation of material results in concentrated destruction and growth of electrical trees. A sharp pin or needle can generate tree structure. The tree structure growth is dependent on different parameters e-g applied alternating voltage, conductivities of walls of gas filled voids, gas pressure in voids, and local field strength of void and frequency of applied voltage. The tree is formed between the two metal surfaces and it is generated at one metal surface. If the tree reaches the other metal surface, it results in complete breakdown of the insulation material because the electric field strength of the remaining healthy portion is too low. Water also affects the electric field strength of insulating material as it is a source of field distortion. It initiates the electric tree which results in breakdown of insulation [24].

4 Designing of OIP bushing of power transformer

4.1 Selection of a 145 kV OIP bushing

- The application for which the bushing is used must be known before selection of bushing. For AC bushings, the surrounding medium on ends of insulation is very important. DC bushings are also developed for HVDC applications.
- The electrical data must be known before selecting the bushing. The electrical data includes highest voltage for equipment, lightning and switching impulse tests, phase to ground voltage at which the bushing is applied and current rating of bushing.
- The bushing must fulfil the ambient and mechanical requirements.

The selection of bushing operating voltage and the conductor diameter is very important in designing of bushing. It should be practical. In this project 145 kV operating voltage is selected as it is practically used in industry. ABB is manufacturing it in Sweden. In this thesis the main purpose is to study the OIP bushing of power transformer which should be common in industry also. The conductor diameter is selected according to ABB data sheet for GOE type 145 kV rating bushing [26]. The bushing is OIP type. This type of bushing is used for equipments with operating voltage above 72 kV. For lower operating voltage resin impregnated papers are used as insulation. Resin impregnated papers are not employed at high voltage because of partial discharge problem [6]. ABB Bushing GOE type data is given below [26]. From bushing data phase to earth voltage and rated current are important.

Table 4.1 145 kV OIP bushing data

Parameters	**values**
Rated Voltage	145 kV
Phase to earth Voltage	83.7 kV
Dry lightning Impulse Test 1.2/50 µs	650 kV
Wet Switching Impulse	500 kV
Rated current	50000 A
Creep age Distance	4775 mm
Mass	410 kg
Height	2500 mm
Conductor diameter	38 mm

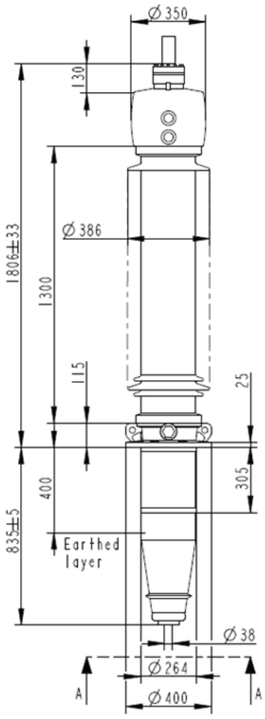

Figure 4.1 OIP 145 kV bushing [26]

4.2 Designing of bushing

After selection, bushing is designed using the data of ABB GOE 650-500-5000-0.6 bushing for power transformer [26]. The designing of bushing is also dependent on material on end of bushing. In this design the upper part of bushing is exposed to air and lower part which is inside the power transformer is exposed to mineral oil. There are some electrical and mechanical design criteria that must be considered but in this thesis only electrical design aspects are considered [10].

- Porcelain is used in the form of sheds. The sheds are made in order to protect surface from rain as much as possible. The dry distance between high voltage and earth is called dry creepage distance. It is underside of sheds. This distance should be 30 mm/kV R.M.S voltage for polluted environment and 16 mm/kV R.M.S for clean environment.
- Total length of bushing on air side must be sufficient to prevent the flashover occurrence. The creepage length must be higher than the length of bushing on air side to prevent the flashover. The arcing horns are provided on air side to divert the overvoltage from porcelain surface so that the porcelain insulation is not damaged.
- Total length of bushing in transformer must be sufficient to prevent flashover in the oil. Flashover can take place at electric field stress lower than the breakdown strength of oil.
- Radial stress is important regarding partial discharge consideration. Radial stress must be limited. For OIP bushing the radial stress should not exceed 3.5 kV/mm for maximum applied voltage, otherwise the partial discharge occurs.

- Larger diameter of conductor is required for high current rating bushings. The diameter of conductor must be enough to limit the radial stress on conductor surface. The value of radial electric stress is given earlier [10].
- As OIP bushing is used so capacitive grading is very important aspect of designing and during capacitive grading, placing and length of aluminium foils are important factors for voltage distribution and radial electric field stress.
- The radial component E_r of the electric field strength can cause insulation breakdown whereas the axial component of the electric field can cause surface discharge along the boundary surface. The axial component is more critical as compared to radial component because the electric field strength of the insulating material stressed to breakdown limit of insulation is higher than the boundary layer stress which results from axial stress to flashover limit. The considerable attention must be given to proper shaping of boundaries so that the inception voltage value for partial discharge is not exceeded [10].
- The current rating of apparatus for which it is used must be considered before designing because the bushing with current rating greater than apparatus increases the temperature inside the bushing [19]

According to bushing data [26] the portion of bushing in air must be 1300 mm long and portion in transformer must be 605 mm. In COMSOL only one side of conductor tube is considered so conductor radius is 19 mm is used. The distance from center of conductor to end of porcelain shed is 193 mm. Porcelain shed is 61 mm thick. The aluminium foils should be arranged such that the same voltage appears across two adjacent two layers.

$$\Delta V = \frac{V}{N} \qquad 4.1$$

N is the total number of conducting layers

4.2.1 Double sided capacitive grading

In double sided capacitive grading bushing, the bushing is graded as a whole whereas in single sided grading both air and oil side bushing is graded separately. In double sided grading bushing, the conducting layers are placed between center of conductor and metal flange. The spacing between the layers is given by

$$s_n = r_n - r_{n-1} \qquad 4.2$$

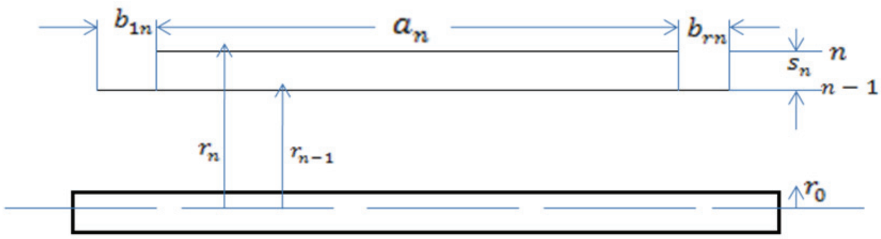

Figure 4.2 Symbols for the calculations of double sided capacitive grading

Symmetrical bushing is obtained if b_{1n} is equal to b_{rn}. The capacitance between two adjacent layers is calculated by

$$c_n = \frac{2\times\pi\times\varepsilon_0\times\varepsilon_r\times a_n}{\ln\frac{r_n}{r_{n-1}}} \quad \text{.........4.3}$$

All capacitors are connected in series so they are equal to one another because ΔV = constant

$$c_n = constant = \mathrm{C}$$

There are two types of grading techniques

- Radial grading
- Axial grading

In radial grading spacing between foil is assumed constant and length of foils is calculated where as in axial grading difference between length of foils is constant and spacing between foils is calculated and it decreases towards metal flange. Voltage can be graded in both the radial and axial direction, but in this project radial grading is used.

The field strength in radial direction must be constant as the spacing between adjacent layers is constant. Assume that $c_{n+1} = c_n$. The length of conducting layer is calculated by recursion formula based on equal capacitance between adjacent layers.

$$C_n = \frac{2\times\pi\times\varepsilon\times a_n}{ln\frac{r_n}{r_{n-1}}}$$

$$C_{n+1} = \frac{2\times\pi\times\varepsilon\times a_{n+1}}{ln\frac{r_{n+1}}{r_n}}$$

$$\frac{2\times\pi\times\varepsilon\times a_n}{ln\frac{r_n}{r_{n-1}}} = \frac{2\times\pi\times\varepsilon\times a_{n+1}}{ln\frac{r_{n+1}}{r_n}}$$

$$a_{n+1} = a_n \times \frac{ln\frac{r_{n+1}}{r_n}}{ln\frac{r_n}{r_{n-1}}} \quad \text{.........4.4}$$

By using the data of preceding foil the length of next foil can be calculated. The innermost radius is known. The spacing between foil is dependent on total number of foils and voltage. The length of preceding foil must be known to calculate next foil length. The shape of foil edges is hyperbolic, along which the potential increases steadily between two adjacent foils. Neglecting the discontinuities produced by conducting foils, the constant value of radial field strength is considered [23].

4.2.2 Designing steps

In this project doubly sided capacitive radial grading is used. The steps for calculation are given below [13].

- First the total numbers of layers are selected. There is no theory available on selection of number of layers for radial grading. For axial grading it is assumed that the voltage between two foil layers should be approximately 12 kV [13], therefore in radial grading same assumption is used, as this value is assumed from industrial experience.
- After numbers of layers selection, the spacing between foils is selected. The radius of conductor is 19 mm. The height of bushing is 2500 mm and total thickness of bushing is 386 mm. Only one side of bushing is considered so thickness from center of conductor to start of porcelain is considered that is 132 mm according to GOE data. The spacing between foils is 11mm. The distance of foils from zero axis on COMSOL is given below and it is in metre, as CMPH setting is in metres
- The spacing between foil is given below

Table 4.2 Spacing between foils of 145 kV bushing model

Position of foils	1	2	3	4	5	6	7	8	9	10	11	12
Spacing between foils, m	0.030	0.041	0.052	0.063	0.074	0.085	0.096	0.107	0.118	0.129	0.140	0.151

- The length of foils is calculated by using the recursion formula given in equation 4.4. The length of first foil is chosen by designer. The length of foils is increasing from metal flange to the center of conductor. The lengths of all foils are given below

Table 4.3 Length of foils of 145 kV bushing model

Position of foils	1	2	3	4	5	6	7	8	9	10	11	12
Length of foils, m	1.90	1.728 5	1.39	1.169	1.007	0.88	0.787	0.711	0.647	0.594	0.549	0.510

- The outermost foil is grounded, so the voltage is distributed between high potential and zero potential. The capacitance is equal between adjacent foils so the voltage between adjacent foil is equally distributed. The radial field strength must not exceed the insulation breakdown strength. Aluminium foils are placed to produce much more homogeneous electric field in radial direction and tangential electric field along bushing surface. The edges of foils make hyperbolic shape of OIP bushing as it is a radial grading.
- The porcelain sheds dimensions are taken according to GOE type bushing of ABB. It is an anti-fog shed with alternating long and short sheds. These shed dimensions are

according to IEC 60815 and these sheds are designed and tested for polluted conditions by ABB [19].

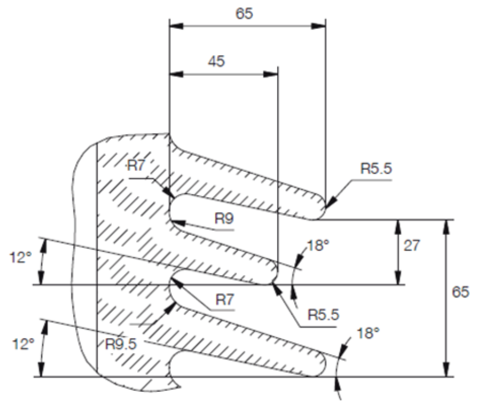

Figure 4.3 Bushing sheds [19]

4.3 Scaled down test model of bushing

In order to perform laboratory measurements on the bushing, a scaled down test model is required because the manufacturing of the full scale bushing in laboratory is very difficult. In test model instead of using 12 foils only three foils are used and the model is scaled down as well. The Scaled down model is such that both radial and axial electric field stress should be close to that of 145 kV designed bushing. To obtain the value of operating voltage the voltage is adjusted in such a way that the axial and radial electric fields in the scaled down model are near to that of the full scale model. The aim is to study the scaled down model in order to manipulate the results for original bushing. The condenser that is hyperbolic portion is immersed in oil. The dimensions of a test model are given below.

The length of first foil is selected and the other values are calculated by using recursion formula given in equation 4.4. The spacing between foil is constant as it is radial grading.

Table 4.4 Dimensions of 5 kV scaled down bushing model

Dimensions	values
Radius of conductor	19 mm
Total foils	3
Total paper + metal foil thickness	10 mm
Spacing between foils	2 mm
Position of first foil from surface of conductor tube	2 mm
Position of second foil from the conductor tube	5 mm
Position of third foil	8 mm
Height	420 mm
Length of first foil	390 mm
Length of second foil	360 mm
Length of third foil	330 mm

5 Implementation of OIP bushing design in CMPH

In this thesis axis symmetric electrostatic mode is used on COMSOL. In electrostatic mode magnetic fields problems are not studied and everything is considered constant with respect to time. The equations related to electrostatic mode are given below.

$$\boldsymbol{E} = -\nabla \boldsymbol{V} \quad \text{5.1}$$

$$\nabla.\mathbf{D} = \rho_f \quad \text{5.2}$$

$$\boldsymbol{D} = \varepsilon.\boldsymbol{E} \quad \text{5.3}$$

$$\nabla.\varepsilon\nabla\boldsymbol{V} = 0 \quad \text{5.4}$$

D is the electric displacement field; **E** is electric field, ρ_f is the charge density and $\boldsymbol{V}$ is the electric potential. There is no charge density so the above equations can be combined into Laplace equation 5.4 and the electrostatic Laplace equation is used to find the electric field distribution around a bushing. In order to solve the electric field problems, field calculation program is required. The mathematical method commonly used in such programs is the finite element method (FEM). This method is used to solve all common types of partial differential equations (PDE) but in this case CMPH it is used to solve Laplace equation which is partial differential equation [3].

5.1 Full scale OIP bushing model in CMPH

The designing procedure is explained in previous section. The bushing is designed on COMSOL Multi physics (CMPH) and the effect of capacitive grading on the voltage distribution and electric field distribution are analyzed in CMPH. During designing in CMPH, the portions of bushing in air and inside the transformer are considered. The oil gauge is neglected. The CMPH conditions and results of 145 kV bushing are given in this section. In the bushing phase to earth voltage of 83.7 kV is used because 145 kV is line to line voltage which is rating of transformer. The steps performed on CMPH are given below.

- 145 kV OIP bushing is designed in CMPH

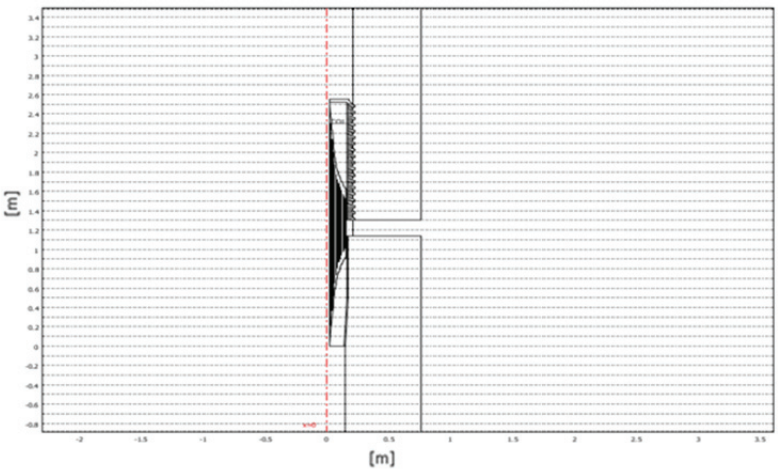

Figure 5.1 Full scale OIP bushing model in CMPH

- After designing boundaries are set, the bushing boundaries along the zero axis which is red in colour and lower part of bushing which is in contact with winding terminal are taken as electric potential. Aluminium foils, OIP boundaries and porcelain sheds are set as continuity because bushing is exposed to air and oil so bushing is continuation of insulation. The air and oil outer boundaries are set as electric insulation. The metal flange and the last foil are grounded.

Table 5.1 Boundary settings

Boundary conditions	Boundary equations
Electric potential	$V = V_0$
Ground	$V = 0$
Electric Insulation	$n.\boldsymbol{J} + n.\frac{\boldsymbol{D}}{T}$
Continuity	$n.(\boldsymbol{J_1} - \boldsymbol{J_2}) + n.\frac{\boldsymbol{D_1} - \boldsymbol{D_2}}{T}$

- Sub domains are defined after setting boundaries conditions.

Table 5.2 Subdomain materials permittivity

Subdomain materials	Relative permittivityε_r
Air	1
Oil	2.2
Porcelain	5.5
OIP	4
Foils	10^8

The region outside the hyperbolic in bushing is oil. The porcelain along oil reservoir sheds and boundaries of oil are considered as separate subdomains. Each foil is set as separate subdomain. The electric conductivity of foils is $6 \times 10^7\ S$. The equation used in subdomain for this mode is given below

$$-\nabla.\left(\left(\sigma + \varepsilon_0.\frac{\varepsilon_r}{T}\right).\nabla V - J^e\right) = \rho_0/\mathrm{T} \qquad \text{.....5.5}$$

In this thesis external current density and space charge density is considered zero.

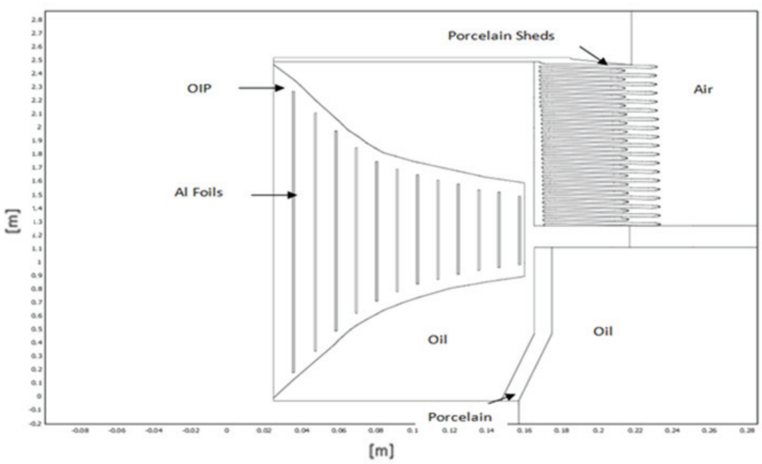

Figure 5.2 Materials in OIP bushing

- The thickness of foils is very small so this model needed a lot of mesh and high processing speed to solve it. After meshing sub domains individually, the model is solved. Because when model is meshed as a unit it gives error.
- After solving the geometry, voltage and electric field distribution along different boundaries are plotted from domain plot parameters in post processing.

5.1.1 Voltage distribution in bushing

The voltage distribution between adjacent foils is given below

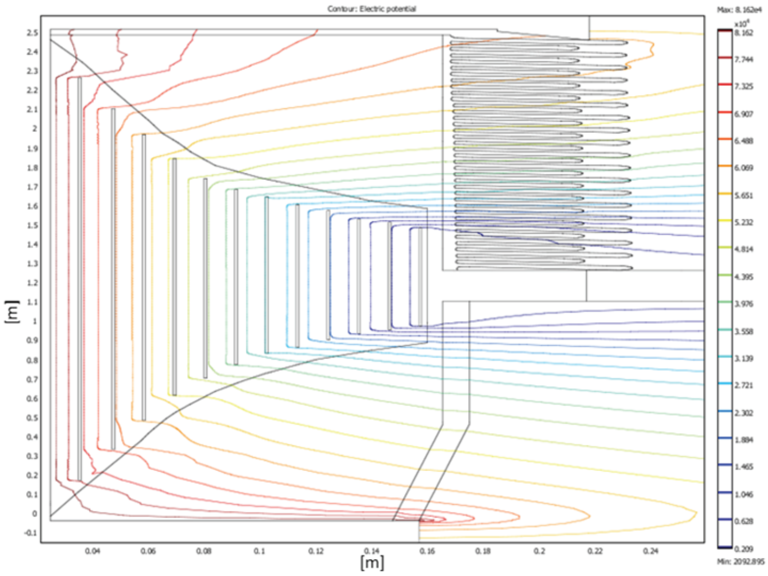

Figure 5.3 Equipotential lines in full scale model

Table 5.3 Voltage distribution between foils of 145kV OIP bushing

Foil number	Voltage(kV) line to earth	Voltage difference between two foils(kV)line to earth
1	72.74	11(between first foil and conductor)
2	63.510	8.8
3	57.15	6.35
4	50.23	6.92
5	43.30	6.93
6	36.95	6.35
7	30.60	6.35
8	24.24	6.35
9	17.85	6.34
10	12.12	5.72
11	5.773	6.34
12	0	5.773

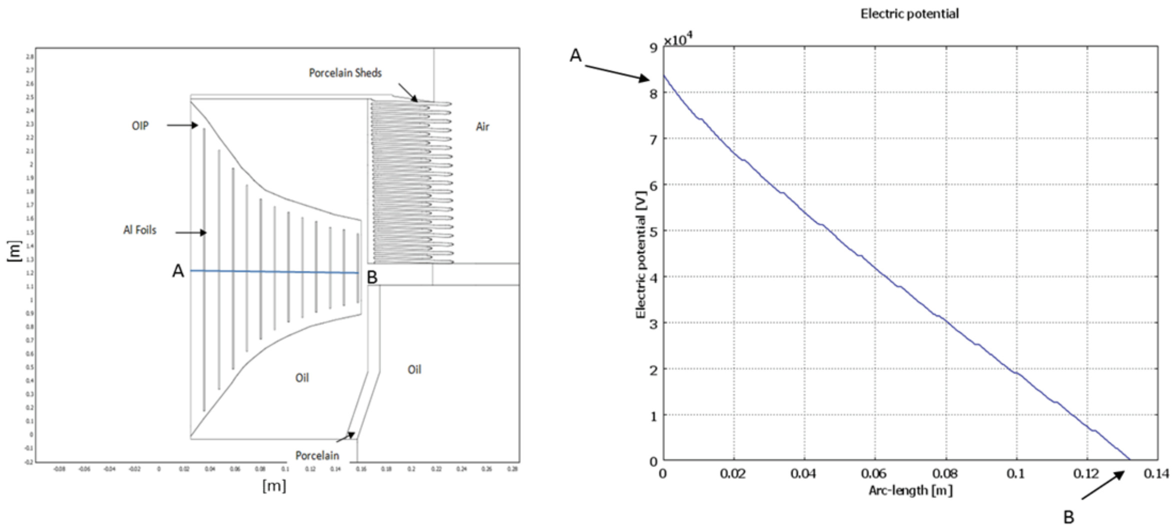

Figure 5.4 Voltage distributions between adjacent foils

From Figure 5.4 it is clear that the voltage at last foil is zero as it is grounded and the voltage is almost uniformly distributed between foils.

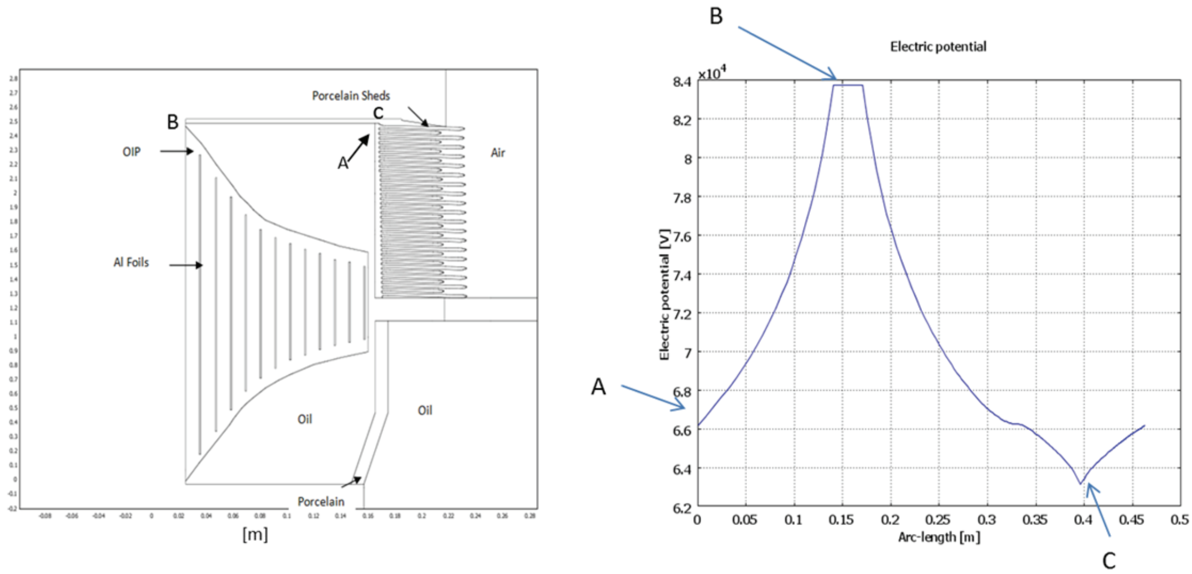

Figure 5.5 Voltage distributions along the oil reservoir side of bushing

The oil reservoir is not considered in CMPH. The oil reservoir is on the upper side of the bushing and it is connected to bushing through porcelain covering. The porcelain is considered in analyzing the voltage distribution as porcelain is insulation and it affects design. The point at which porcelain touches the high potential is a straight line of 83.7 kV and as insulation is far from high potential conductor, the voltage again decreases.

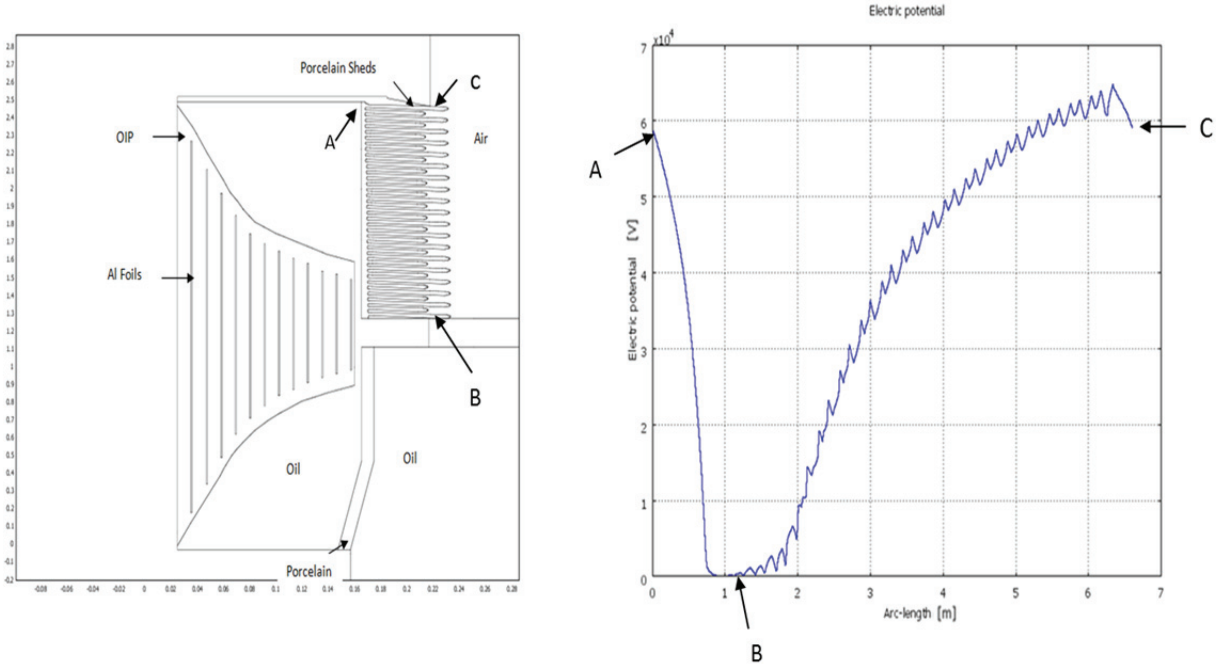

Figure 5.6 Voltage distribution along the porcelain sheds

The porcelain sheds are touching the ground so voltage at that point becomes zero. From Figure 5.6 it is clear that there is a variation in voltage along the sheds because of its shape and difference of insulations as sheds are in air.

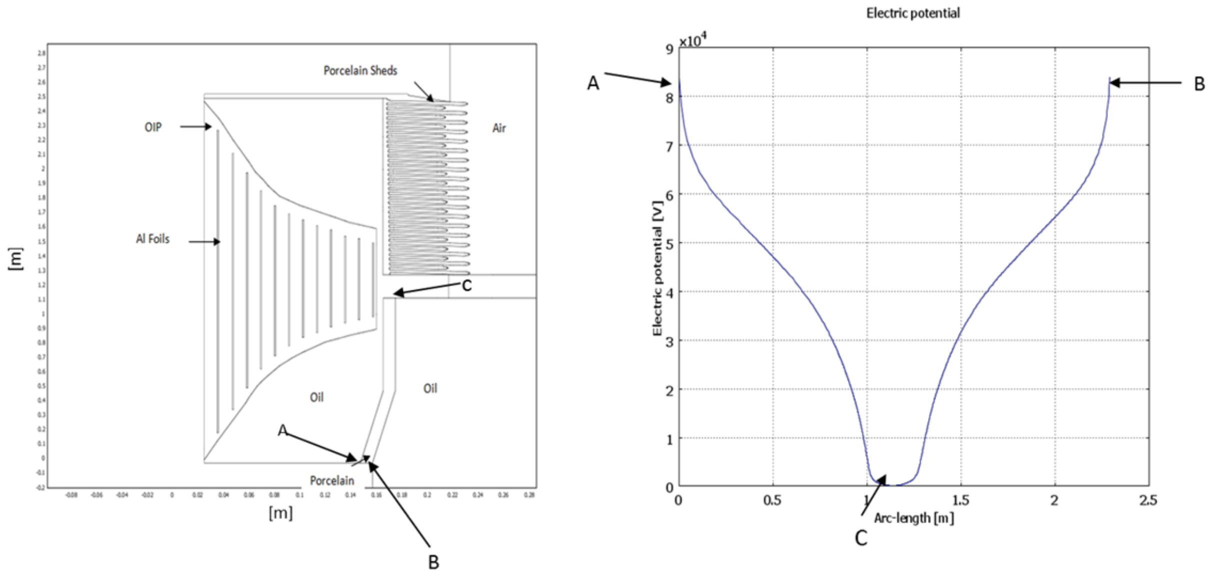

Figure 5.7 Voltage distributions along the porcelain on oil side of transformer

When porcelain on oil side of transformer touches the ground, voltage becomes zero. The insulation on both sides of porcelain is oil so there is no variation like sheds as shown in Figure 5.7.

5.1.2 Electric field distribution in bushing

The electric field distribution is very important aspect of bushing so before implementing any design the field distribution is analyzed. Radial electric field is in x axis, axial field is in y axis and tangential component is analyzed along the surface of geometry. The tangential component is made up of radial and axial electric field. It is given by [11].

$$E_t = abs(V_x \times t_x + V_y \times t_y) \ldots\ldots\ldots\ldots 5.6$$

$$\boldsymbol{t} = (t_x, t_y) \text{ and } \boldsymbol{E} = (\frac{\partial U}{\partial x}, \frac{\partial U}{\partial y}) \text{ and } E_t = \boldsymbol{E} \cdot \boldsymbol{t}$$

Where t_x and t_y are components of tangential vectors on the boundaries and V_x and V_y are derivatives of voltage. In this thesis only absolute value of tangential electric field is required.

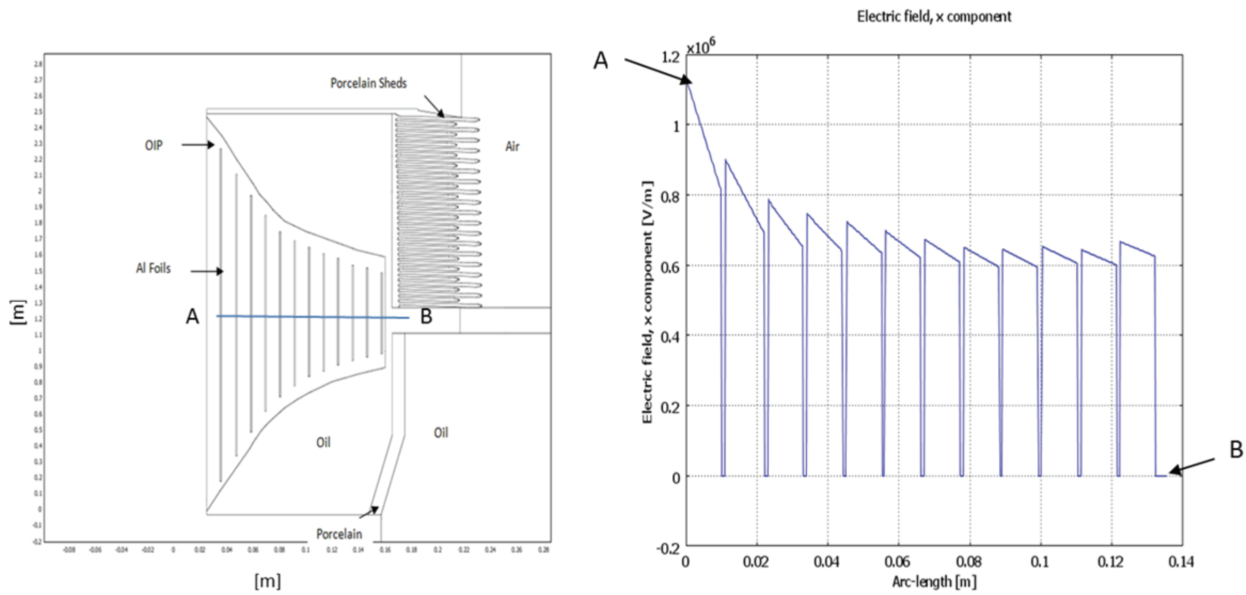

Figure 5.8 Electric field distributions along radial-axis in full scale bushing

The radial electric field E_r is uniformly distributed between foils as the voltage is uniformly distributed. E_r inside each foil is zero as these are metallic foils. The last foil is grounded so radial electric field becomes zero. These foils are used to distribute the radial electric field inside the insulation so there is no particularly concentrated electric field stress at one point in insulation.

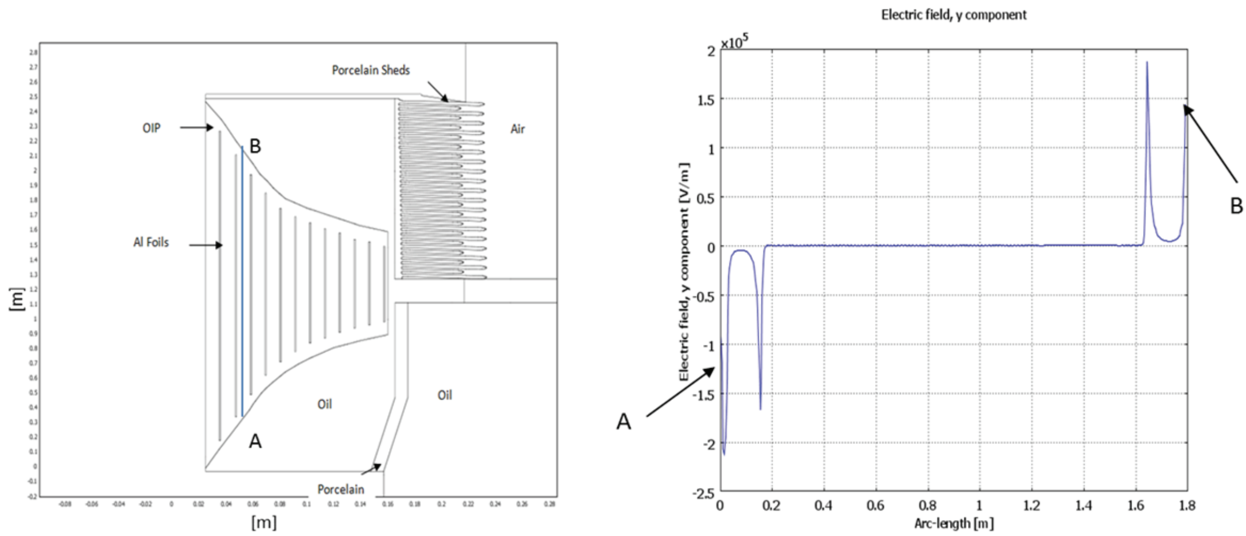

Figure 5.9 Electric field distributions along the axial axis in full scale bushing

The axial electric field $E_a$is zero inside the hyperbolic region of bushing as it is straight line on the graph. There is axial electric field stress only on the edges of foil. Inside the OIP there is radial electric field distribution. E_a at edges is very critical as stress at these edges can result in surface discharge.

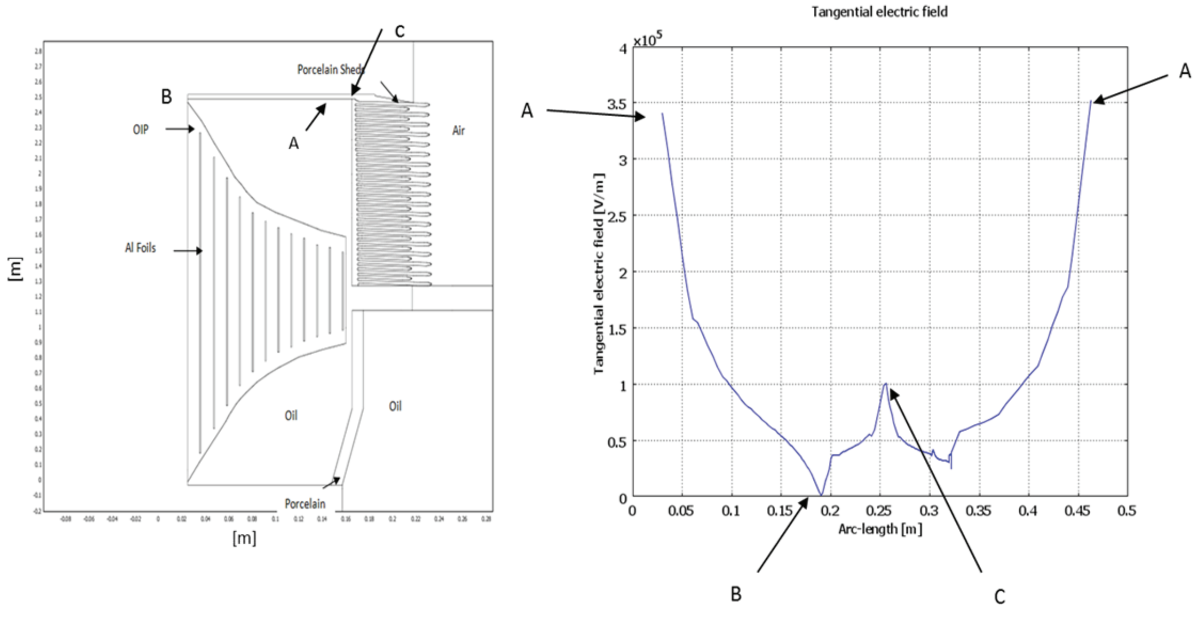

Figure 5.10 Tangential electric field along the oil reservoir side of bushing

The tangential electric field stress occurs at edges of oil reservoir side insulation as shown in Figure 5.10.

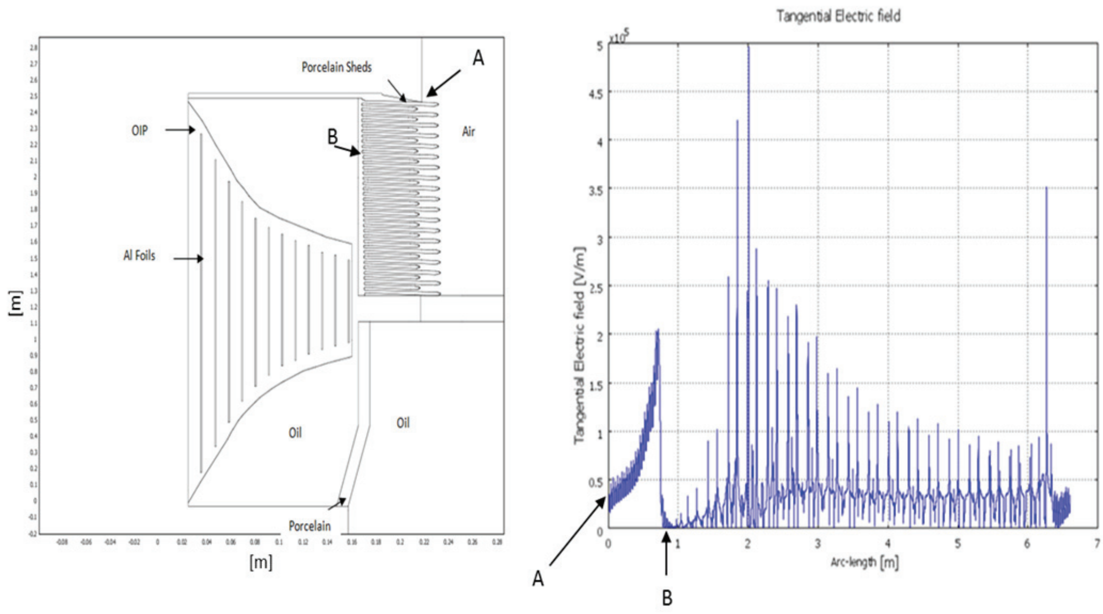

Figure 5.11 Tangential electric field along porcelain sheds

Porcelain sheds are exposed to air so there is a difference of insulation material at boundaries and sheds have lot of bends so tangential electric field stress is higher at these edges as shown in Figure 5.11.

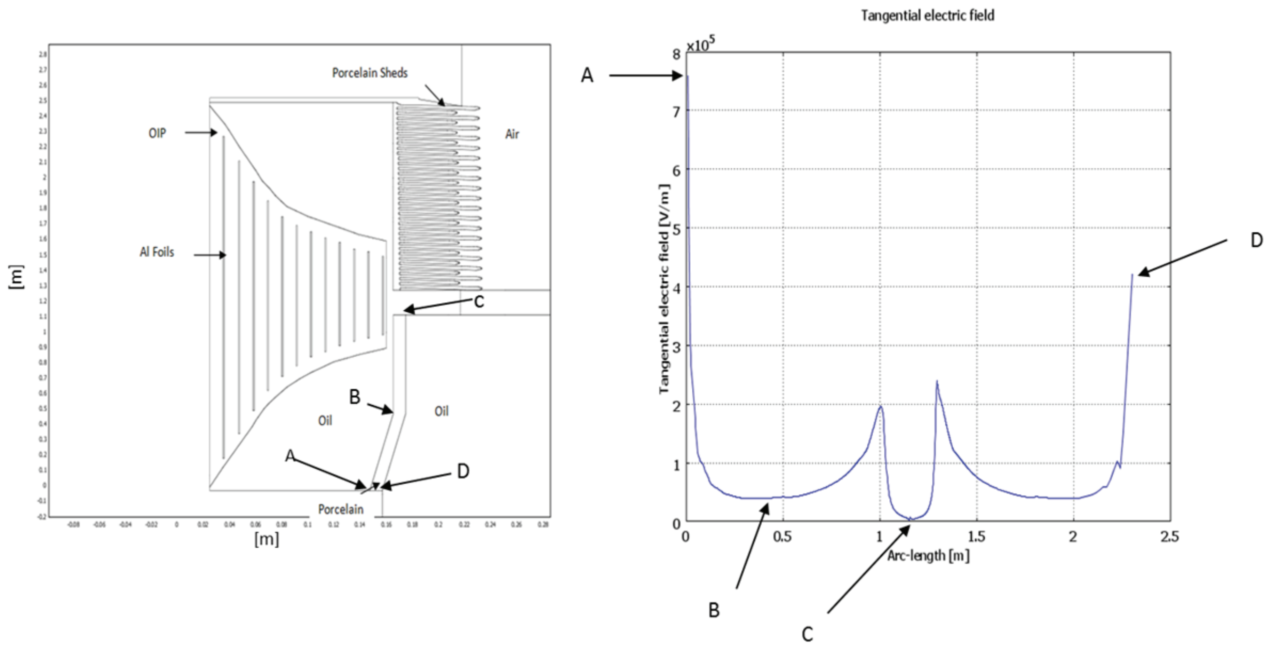

Figure 5.12 Tangential electric field along the porcelain in transformer

From Figure 5.12 it is clear that the porcelain which is a solid material of bushing is heavily stressed by tangential field intensity E_t as it shares boundaries with oil on both sides. There are dips because of bends in the geometry.

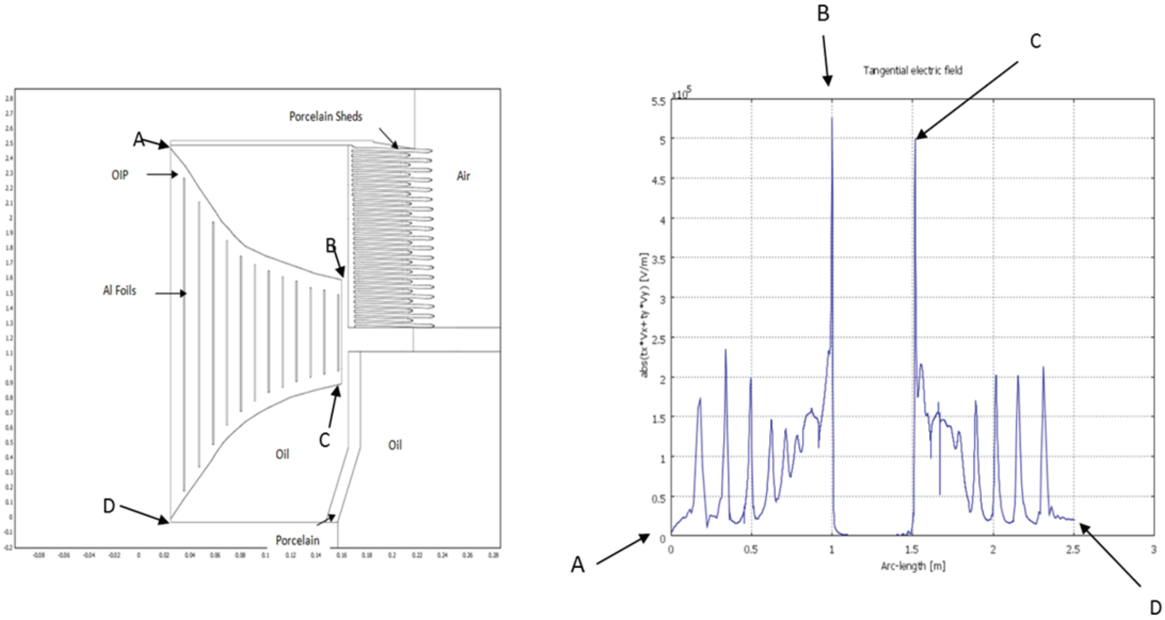

Figure 5.13 Tangential electric field along OIP

There is a tangential electric field E_t along the hyperbolic region of OIP but as the OIP becomes parallel to foils the tangential electric field is zero. E_t After last foil there is an end of hyperbolic boundary and there is a sharp edge so stress is maximum at this point.

5.2 Scaled down bushing model on CMPH

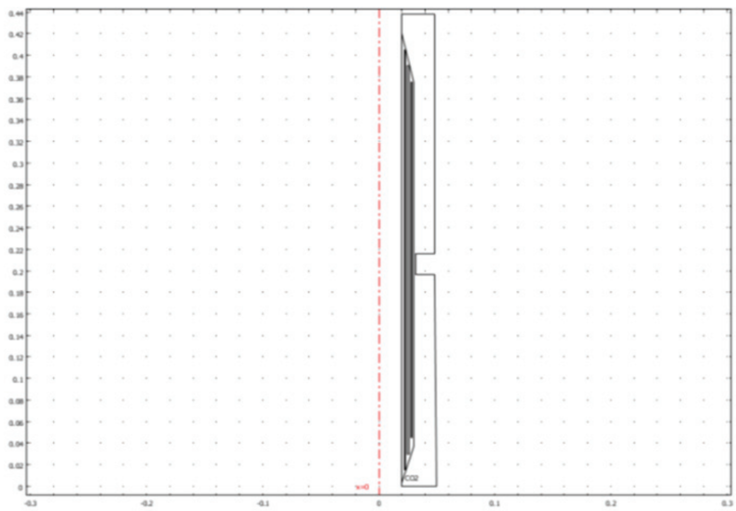

Figure 5.14 Scale down test model

In test model porcelain is not used. The model is immersed in oil tube and the last foil is grounded. Foils and boundaries of hyperbolic part are given continuity condition as these were inside the oil which is insulation. The outer boundaries of oil are set as electric insulation condition. There were five sub domains as foils are considered as separate sub domains with high relative permeability of 10^8. The hyperbolic region is given relative permeability of 4 and mineral oil 2.2.

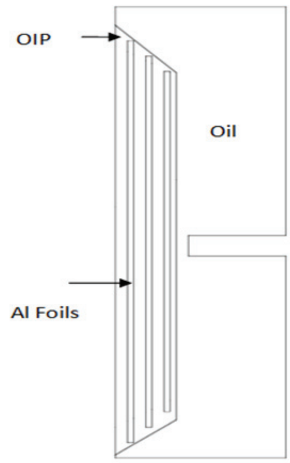

Figure 5.15 Materials used in test model

5.2.1 Voltage and electric field distributions

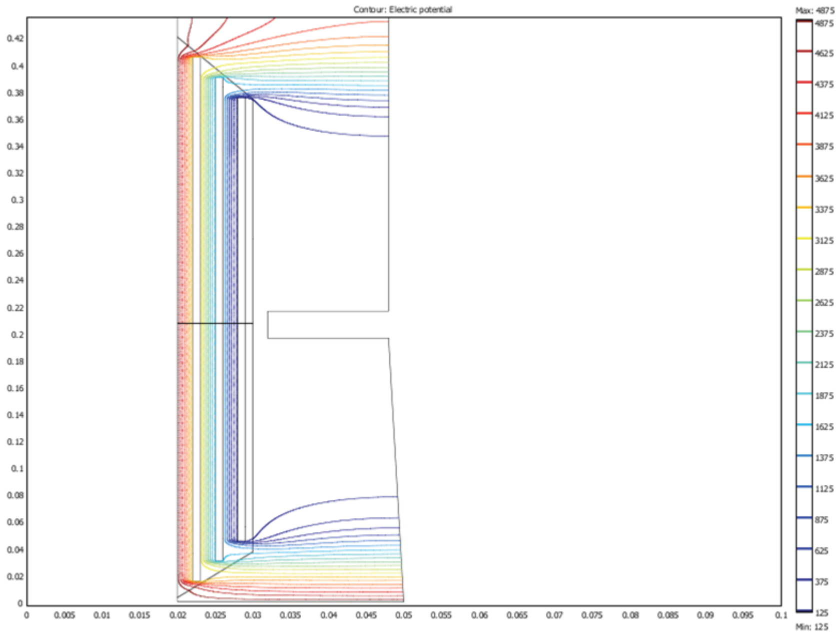

Figure 5.16 Equipotential lines in test model

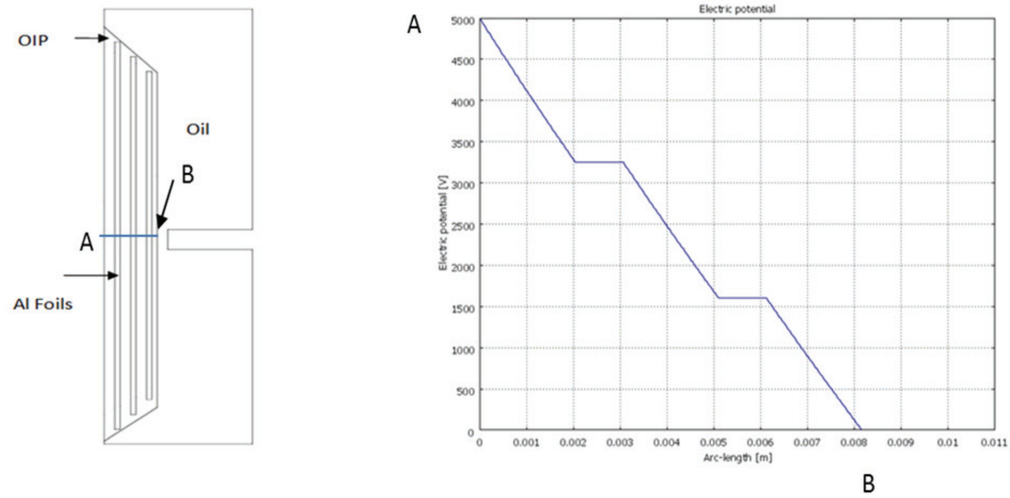

Figure 5.17 Voltage distributions between foils

From Figure 5.17 it is clear that the voltage is uniformly distributed between the foils and it is zero at the last foil as it is grounded. The voltage is line to earth.

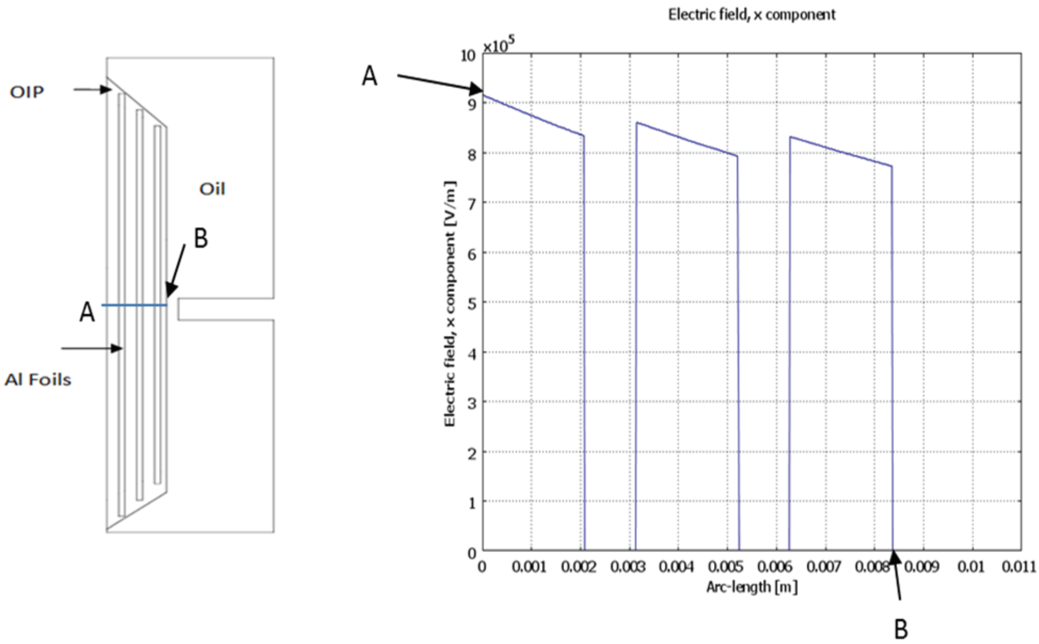

Figure 5.18 Radial electric field in test model

From Figure 5.18 it is clear that the electric field is uniform between foils as the voltage is uniformly distributed between foils. At each foil electric field is zero as these are metallic foils. These foils are used to distribute the electric field inside the insulation therefore there is no radial electric field stress at one point in insulation.

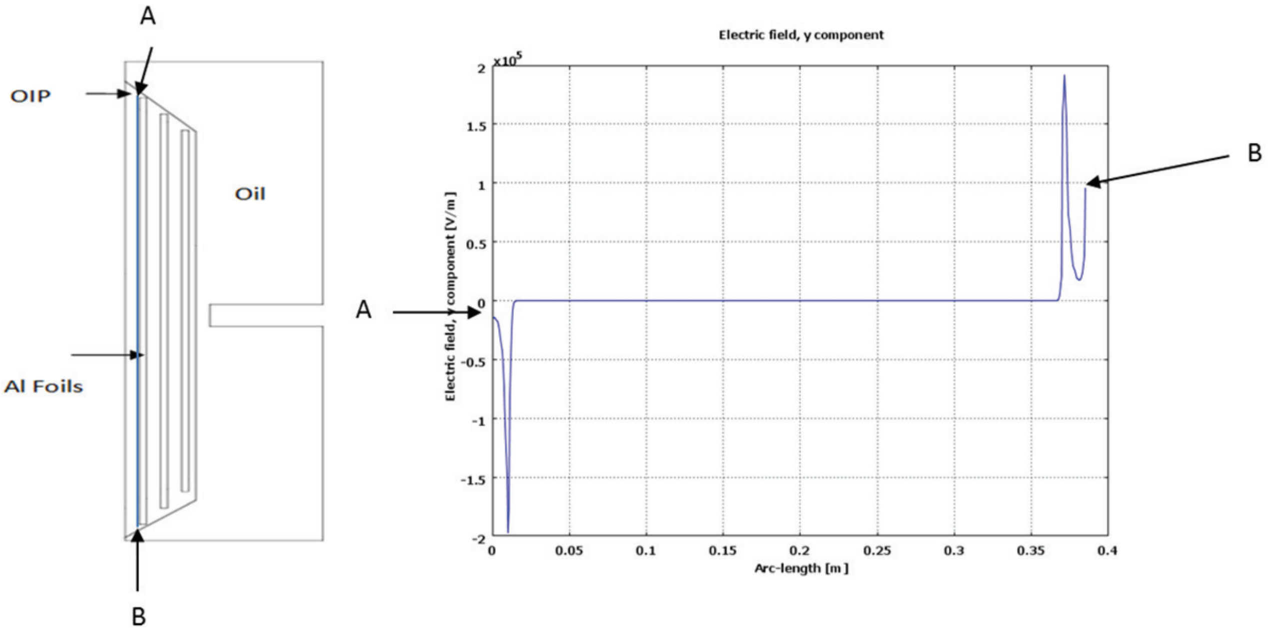

Figure 5.19 Axial electric field in a test model

From Figure 5.19 it is clear that the axial electric field distribution is only on the edges of foils. The stress at these edges can result in surface discharge.

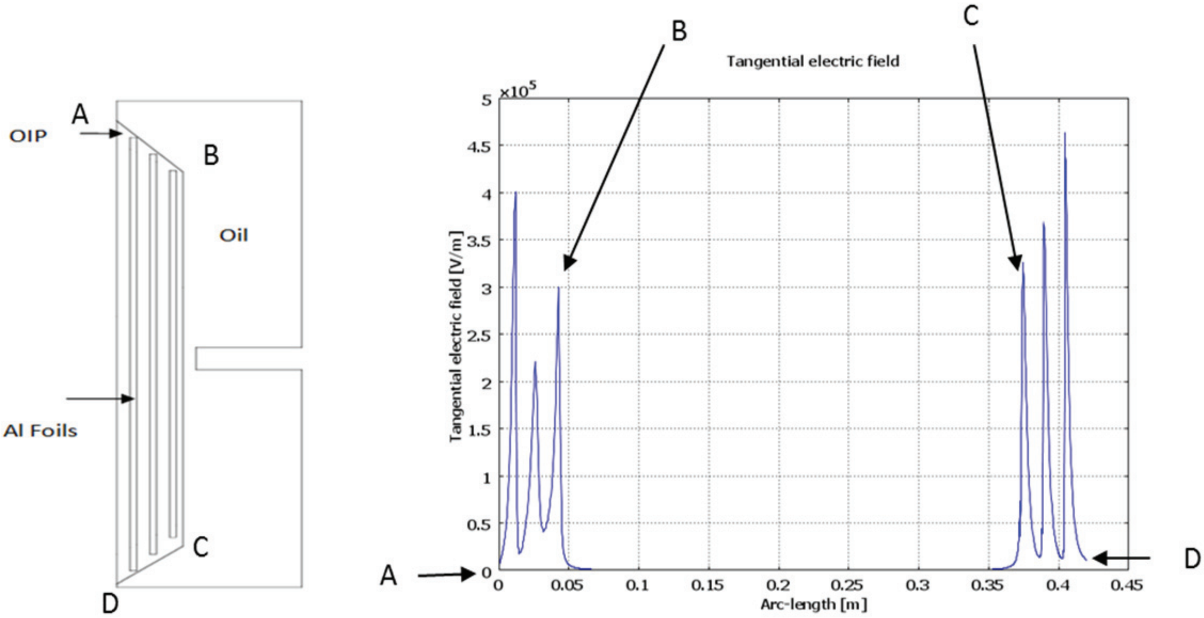

Figure 5.20 Tangential electric field along OIP boundary of test model

From Figure 5.20 it is clear that the pattern is same as that of 145 kV bushing model. The tangential electric field parallel to foil becomes zero.

6 Partial discharge measurement in oil impregnated paper bushing test models

6.1 Measurement introduction

The measurements of partial discharges are used to detect the causes of degradation in insulation of high voltage power system. The measurement of PDs is important for quality control of electrical equipment. The partial discharge is considered as a symptom for degradation and defects in high voltage insulation. In this project the partial discharges were measured on test models by the use of an insulation condition monitoring system (ICM). The purpose of these laboratory experiments on the test model was to study the signature of partial discharge in the OIP bushing. The test model was made up of oil impregnated papers and metallic foils at calculated radial distance. The papers were impregnated in the laboratory. After making the model the PD measurements were performed.

There are chances of PD in measurement system as PDs are measured at high voltage e.g. internal discharge in voids or corona on sharp electrodes. The system is very sensitive to disturbances in the surrounding environment. The electromagnetic interference disturbs the partial discharge measurement. It should be ensure that the measurement system is PD free. PD is measured on the basis of maximum partial discharge magnitude which is called PD level. A higher PD level shows that insulation is more defected. From analyzing PD at opposite polarity of applied voltage it is possible to detect the cause of PD as explained in chapter 2.

6.2 Paper impregnation

Test model preparation of bushing includes the impregnation of paper as the bushing insulation is oil impregnated paper. The oil impregnation of paper increases the breakdown strength of paper. The papers are wrapped in the form of layers on the conductor. The relative dielectric constant of oil impregnated paper is dependent on the permittivity of mineral oil, permittivity of paper which is made up of cellulose fibers and density of paper. The dielectric constant of oil impregnated paper varies between 2 to 4 depending on the paper density and impregnation. The paper normally used for insulation purposes is a special variety of paper called Kraft paper. Papers and paper boards are produced from cotton and organic fibers. If the thickness of paper is more than 0.8 mm then it is called paper board. The high thickness paper boards are called press boards and these are prepared by lamination of many layers of papers. These are used as supporting material and insulating barriers in transformers [22].

The paper is hygroscopic so it needs to be dried and impregnated before being used as insulation either in bushing or inside the transformer. In this thesis papers were impregnated with mineral oil of permittivity 2.2 to 2.3. The permittivity of paper before impregnation was 2.1 and after impregnation permittivity was increased to 3. The procedure to impregnate the paper is given below.

- Papers are dried in vacuum at 120 °C for 24 hours
- Cool down to 60 °C, flow with dry air, open chamber and oil is inserted that is heated to 60 °C.
- Vacuum is pumped and oil is degassed for 24 hours.
- Dry air is flowed, chamber is opened and papers are immersed in oil, vacuum is pumped again and impregnated for 24 hours.
- Heating is turned off and impregnated papers are cooled to room temperature for 24 hours before taking them out.

Note

Impregnation must be done carefully because faulty impregnation results in large size cavities

6.3 Measurement setup

The measurement part is divided into two parts [28]. The high voltage part is inside the cage for safety reasons whereas low voltage part is outside the cage to control the voltage and to take measurements.

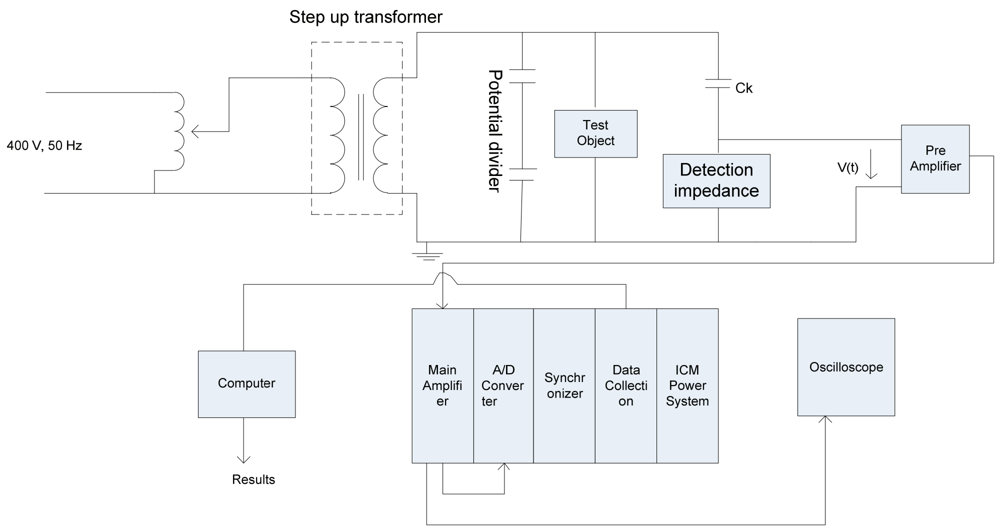

Figure 6.1 PD measurements setup with ICM (Insulation Condition Monitoring) system

6.3.1 High voltage part

The high voltage part containing test model needs special care so that there is no source of partial discharge from measurement system. The high voltage part consists of a variable transformer, step up transformer, a potential divider, a coupling capacitance, and test object. A voltage from variable transformer is controlled from bench knob. When there is partial discharge in test model, coupling capacitance C_k of 1000 pF act as stable voltage source as it injects the apparent charge into a test object. The coupling capacitor directly connected to test model bushing is used as coupling device. The coupling capacitor must be free from discharges upto maximum test voltage otherwise it is not possible to distinguish between discharges from test model and coupling capacitor [10]. From coupling device discharge signals are transmitted to detection circuit through cable [29]. During partial discharge the current passes through coupling capacitance to test model. The apparent charge is not same as physical charge .The apparent charge is transmitted from coupling capacitance to test model where as physical charge is the result of discharge inside the test model [28]. When apparent charge is injected into the test object it temporarily changes the voltage in test object by same amount as physical charge does. The discharge in test model is detected by apparent charge transfer into test model [10].

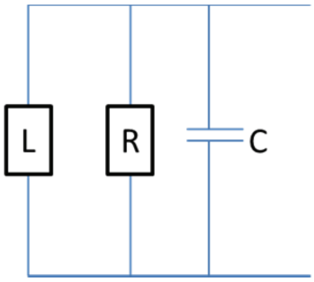

Figure 6.2 Detection impedance

6.3.2 Low voltage part

The low voltage part consists of computer, detection impedance, preamplifier, oscilloscope and ICM system which is used to record partial discharge. Detection impedance circuit is in series with the coupling capacitance. It has very high sensitivity and it is used to detect the partial discharge by measuring the time dependent voltage. The input voltage is given to preamplifier. The pre amplifier integrates over a cycle and it is used to amplify the signal [10]. It has the frequency of 1 MHz and fairly wide bandwidth. The time dependent measured signal from the pre amplifier is sent to the main amplifier of the ICM power system. From the main amplifier the amplified time dependent measured signal is sent to A/D converter and in end to oscilloscope. As a result of integration by pre amplifier, the peak discharge magnitudes are recorded on ICM system. The ICM system records the peak discharge magnitudes. The synchronizer is used to determine the phase position of measured signal relative to applied voltage. The signal is then passed to data collection unit and in the end to computer through general purpose interface bus. Oscilloscope is used to measure the inception voltage and ICM system is used to record the PD pattern. These PD patterns can be extracted from ICM files using MATLAB.

6.3.2.1 Insulation condition monitoring system (ICM)

It is commercially available insulation monitoring system; it is developed by "**Power Diagnostix Systems GmbH**" company from Aachen Germany. In this thesis it was used to record partial discharges pattern in the test model of a bushing. The ICM has many modules and these modules perform amplification, recording of PD pattern, analog to digital conversion and communication with a computer. The general purpose interface bus is used to connect the ICM system and control computer. The amplified signal from preamplifier is feed into the main amplifier in the ICM system. In the main amplifier module the peak meter measures the voltage peaks that are related to apparent charge. The peak meter only measures the magnitude of peaks. Analog digital converter is used to provide phase resolved patterns. The ICM modules settings are controlled from control computer through general purpose interface bus. All settings and commands can be change from computer [30].

6.4 Partial discharge measurement on paper samples

In order to analyze the partial discharge in impregnated papers the measurements were performed on papers in special setup in which paper samples were placed in between the H.V connected electrode and the earthed electrode and the test setup was filled with oil [31]. Four papers of equal size were chosen with foil between layers.

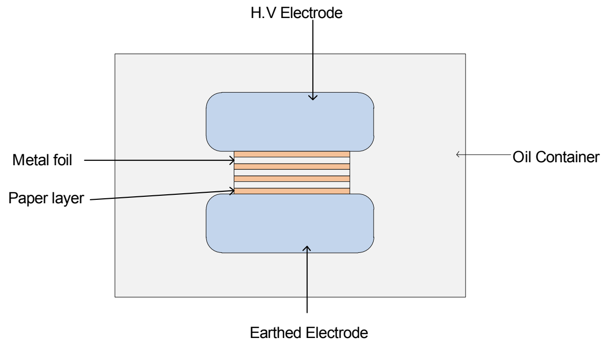

Figure 6.3 Schematic diagram of paper samples setup

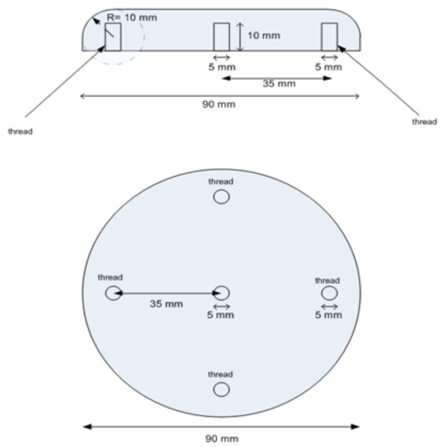

Figure 6.4 Dimensions of electrodes in paper samples setup [31]

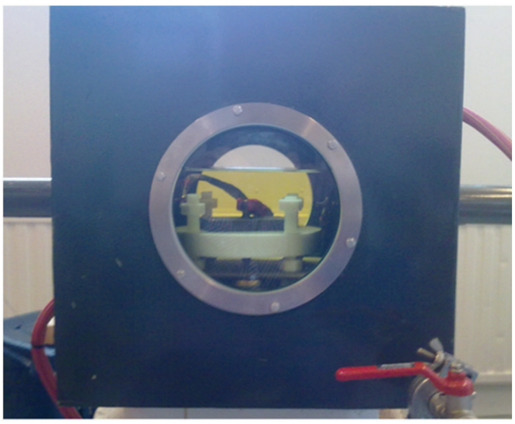

Figure 6.5 PDs measurement setup for paper samples in oil [31]

6.4.1 Measurements with uncovered electrodes

The foil size is very important because improper placing of metal foils can result in large magnitude of PDs therefore small size of foils were used as compared to paper size. The papers and foils were arranged inside the oil container.

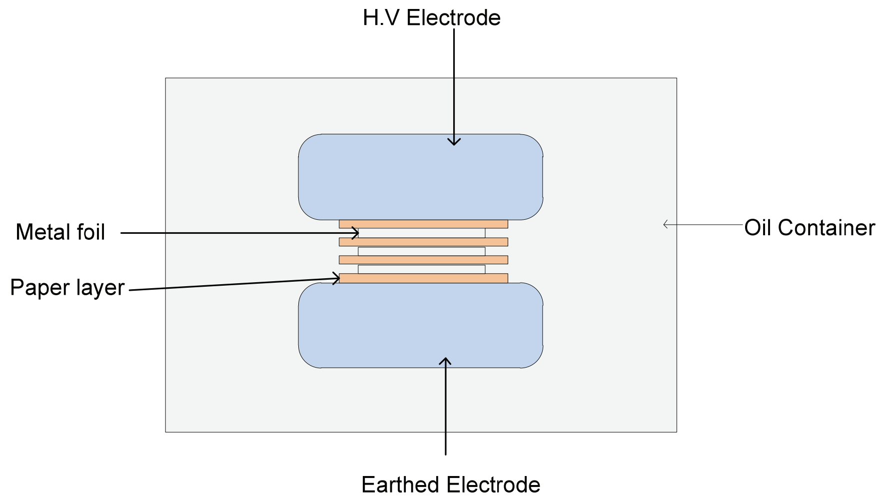

Figure 6.6 Schematic diagram of Paper samples with metal foils

Inception voltage= 3.5 kV PDs pattern was recorded at 4 kV

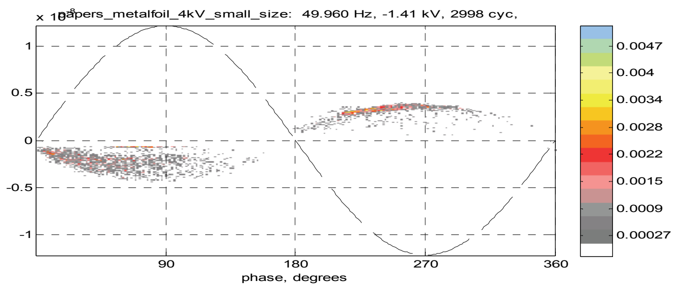

Figure 6.7 PD pattern for paper samples with metal foil of smaller size

From Figure 6.7 it is clear that the pattern is the result of edge discharges of top and bottom electrodes as the electrodes were inside the oil insulation. When electrode is perpendicular to insulation and it is inside the insulation the edges of electrode create severe local electric field buildup which results in local partial discharge which destruct the solid insulation. It is same in oil immersed insulations [4]. Corona also occurs from these edges.

When foils of same size as papers were used, partial discharges were recorded at 4 kV. The pattern was same because the papers and the foils were arranged between electrodes inside the oil so there was no chance of gas bubbles and the source of PD was not from a metallic foil. The discharges per cycles are more than the small foils PD pattern.

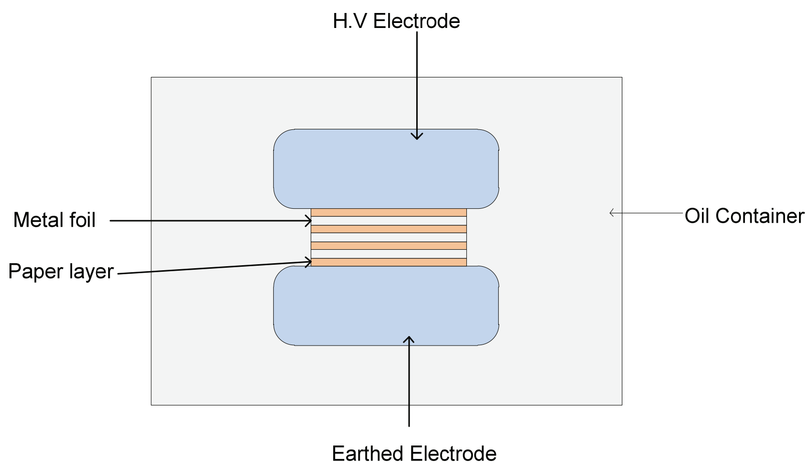

Figure 6.8 Schematic diagram of paper samples with metal foil of same size

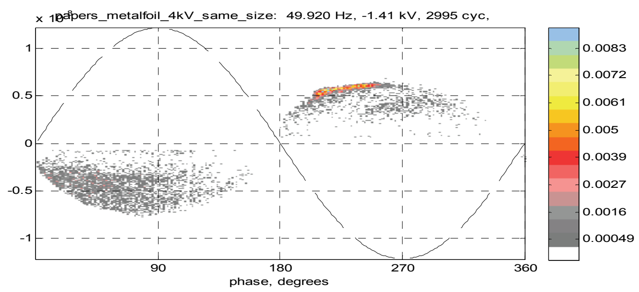

Figure 6.9 PD pattern for paper samples with metal foil of same size

From Figure 6.9 it is clear that the pattern is the result of edge discharges from the electrodes and corona. There are no gas bubbles patterns in figure. The edge discharges occurred because the size of papers was smaller than the electrode size and the edges created local electric field buildup which resulted in PDs.

6.4.2 Measurements with paper shaded electrodes

The electrodes were shaded with paper and the papers were arranged with foils inside the test setup. The voltage was raised to 15 kV but no partial discharge was observed. If the voltage was increased further then there was a chance of complete breakdown. In this case the electrodes were covered with papers therefore when voltage was increased the partial discharge did not occur as the papers have high electric field strength than oil and there was no buildup of a local electric field. There was no PD even without the foils between samples.

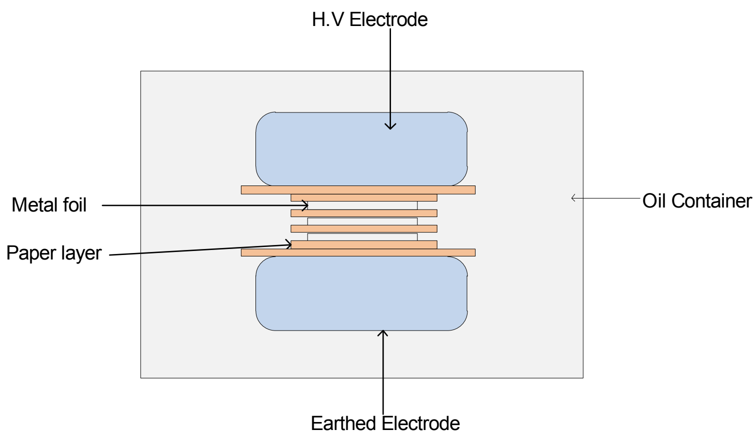

Figure 6.10 Schematic diagram of paper samples measurement setup with shaded electrodes

Note:
From these results it can be concluded that the discharges were also occurring between foils and electrodes as the distance between foils and electrodes was very small. In case of same size foils the numbers of discharges in pattern is more than with small size foil PD pattern. But after covering the electrodes with papers there is no discharge pattern.

6.5 Partial discharge measurement on test model with three foils

The test model of oil impregnated bushing was made in laboratory by wrapping papers on a conducting tube with foils at predetermined radial distance. The model was made with loose wrapping so there were a lot of gaps in between the paper layers. The scaled down OIP bushing model was placed inside the tube.

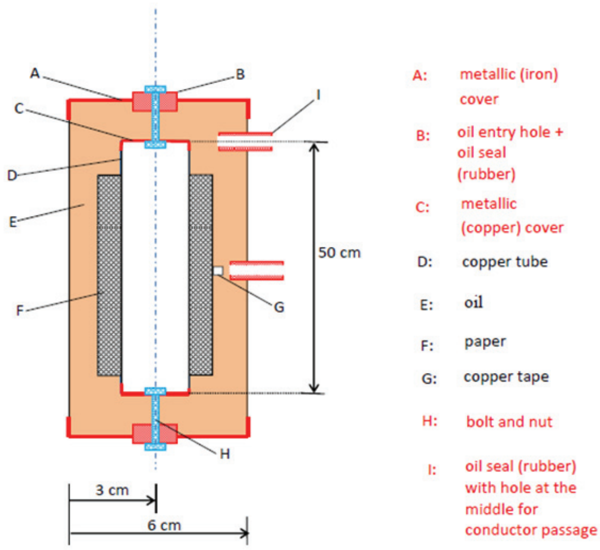

Figure 6.11 Adjustment of scale down bushing test model in oil tube

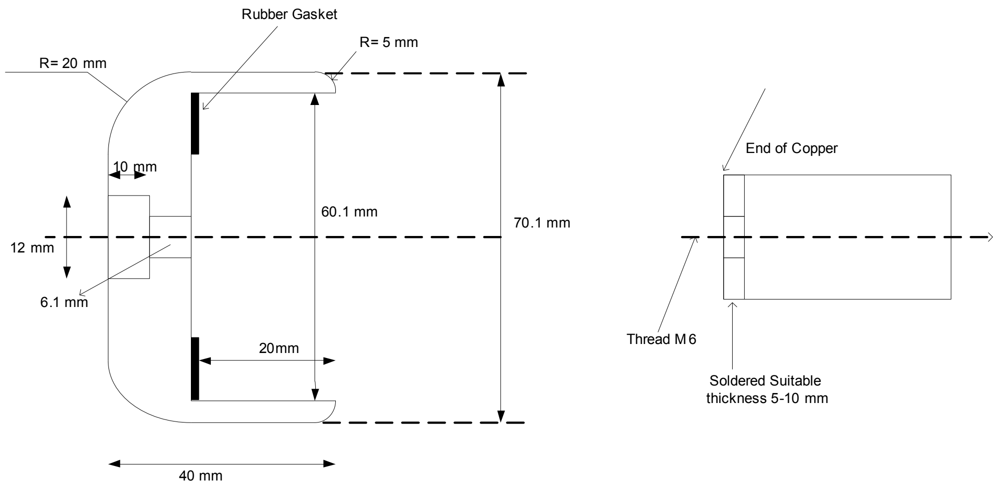

Figure 6.12 Dimensions of copper covers of oil tube

Figure 6.13 Scaled down OIP bushing model

The measurements were taken without inserting oil in tube.

The Inception voltage without oil= 6.5 kV and the PDs were recorded at 8 kV

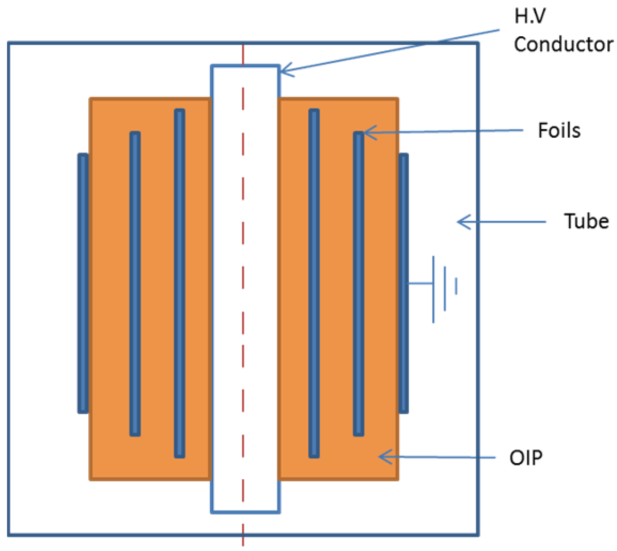

Figure 6.14 Schematic diagram of foils arrangement in bushing test model

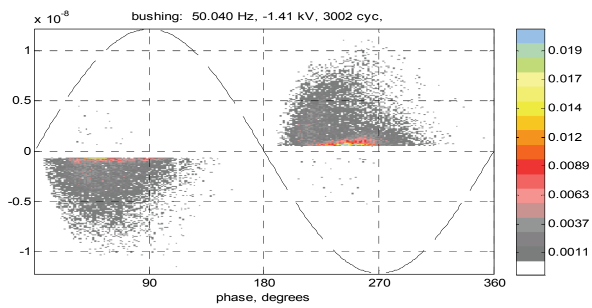

Figure 6.15 PD recorded for test model with loose paper layers without oil in tube

From Figure 6.15 it is shown that the pattern is the result of corona from the foil edges and voids between the paper layers. In case of gas filled voids in solid insulations, the PDs pattern occurs between at the zero crossings and the peaks of both half cycles. On an average the amplitude of pattern is the same in both half cycles.

After recording the PDs, the tube was filled with oil and moved up and down for some time to fill the gap between the paper layers with oil. Again the inception voltage was recorded.

Inception voltage= 8.5 kV

The PDs were recorded at two different voltages 10 and 12 kV in order to observe the voltage effect on partial discharges.

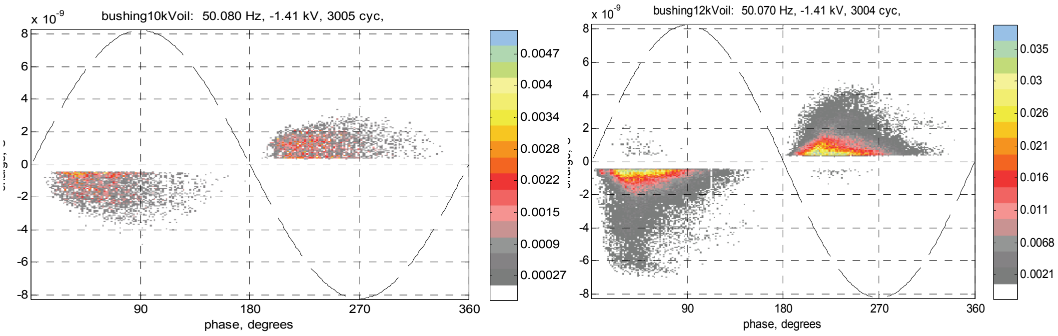

Figure 6.16 PD pattern for scale down bushing model with oil in tube at 10 and 12 kV

From Figures 6.16 it can be observed that there is a substantial symmetry in patterns, as the PD pattern is observed in both half cycles. The PD pattern is the result of surface discharges from foil edges in the oil and gas bubbles in insulation. During recording the acoustic noise was noticed after 11 kV because of the corona from foils. By increasing the voltage the partial discharges were increased. At higher voltage surface discharges converts into corona. The PD pattern from corona in oil occurs in both polarities but the amplitude is larger in positive polarity. Gas bubbles in oil do not have a stable pattern because gas bubbles disintegrate.

When bushing test model was placed in vertical position for long time and moved up and down, many gas bubbles were removed from papers as gas bubbles moved up and then removed, the inception voltage was increased to 11 kV but the pattern was same.

The ICM power system was used to record the partial discharge pattern as it was connected to an oscilloscope. In an oscilloscope the PDs were recorded in a form of lines. There was an applied voltage and signal from test set up to oscilloscope, the discharges in the form of lines were observed after inception voltage. These patterns were recorded in the ICM power system. In the ICM system amplitude of the gain was adjusted in order to observe the pattern in a good way. But if the gain is increased too much the saturation takes place so in that situation a gain needs to be decreased. During recording of discharge pattern without oil there was no problem of saturation but during measurements with oil filled tube the saturation was occurred therefore a gain was decreased but still the pattern was saturated. The test setup was calibrated again and the detection impedance was changed to 100 Ω and test setup was calibrated at 1000 pC. Earlier without oil, the detection impedance was 1 kΩ. After changing in values the gain of ICM Power system was 4.

Note:

- Because of coupling capacitance the PD pattern is shown in opposite polarity as the direction of current is reversed.
- The Corona in air can occur in both polarities depending on a sharp point location. If the sharp point is on the high voltage part then the corona in an air occurs in negative half cycle and if sharp point is on an earthed foil then corona occurs in positive half cycle [10].

- The occurrence of partial discharge is dependent on the local electric field, geometric shape of bubble, cavity or any other cause of partial discharge and the availability of starting electrons. The availability of starting electrons is dependent on the placing of metallic foil, insulation material and the distance of defects from the metallic foil. [29].
- When the thickness of insulation is increased as the papers layers are increased after each foil the electric field gradient is reduced which results in change in partial discharge behavior and also when the voltage stress or applied voltage is removed it provides some recovery of insulation [5].
- The partial discharge inception voltage is dependent on the thickness of oil, the impregnated papers and dielectric constants of both the oil and impregnated papers.

6.6 Partial discharge measurement on test models after wrapping each foil

6.6.1 Partial Discharge Measurement on scale down test model with one foil

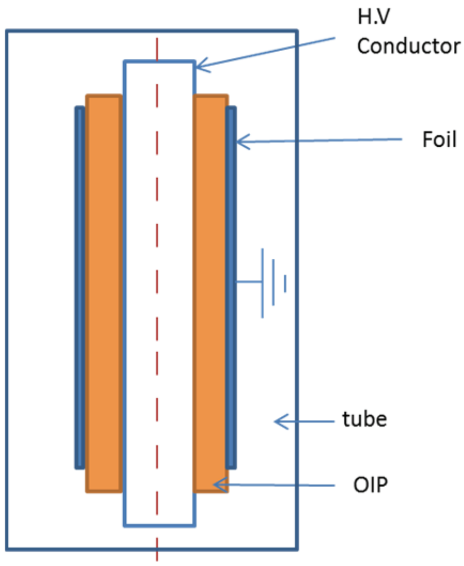

Figure 6.17 Schematic diagram of test model with one foil

The papers were well wrapped on conducting tube until the first foil. There were few voids as it could not be avoided but less than the first wrapping. After this it was placed in tube without filling any oil in it.

Inception voltage = 2.50 kV and the PD pattern was recorded at 3 kV.

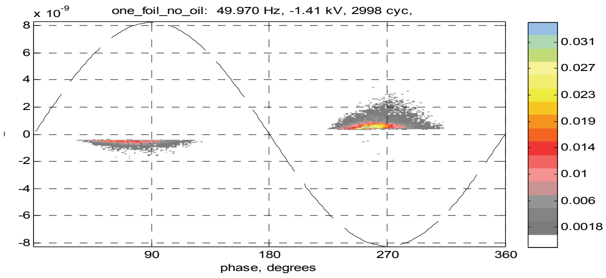

Figure 6.18 PD pattern for one foil test model without oil in oil tube

From Figure 6.18 it is clear that the partial discharge pattern is the result of corona in air and voids between paper layers because the corona pattern is symmetric with respect to peak of applied voltage. At higher voltage it can occurs in positive polarity also.

After this the oil was inserted in tube. The tube was not completely filled with oil so that there should be space for bubbles to come out. There were few gas bubbles in tube .The tube was placed vertically so that most of the gas bubbles came up. The foil was earthed.

Inception voltage= 3.8 kV and PD pattern was recorded at 4.5 kV

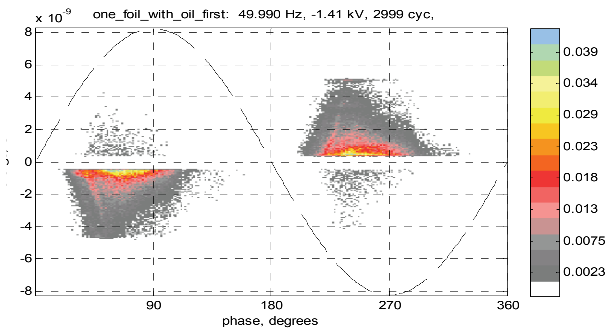

Figure 6.19 PD pattern for one foil test model in oil filled tube

From Figure 6.19 it is shown that the pattern is a combination of surface discharges from foil edges and gas bubbles in solid insulation and oil. The gas bubbles in oil were disintegrated. The pattern occurs in both polarities. PD pattern is saturated and overshoots occur.

The tube was placed vertically for 30 minutes in order to remove the gas bubbles. After 30 minutes the measurement was taken again, as many bubbles were removed from papers the inception voltage was measured and PD was recorded at same voltage. Gas bubbles disintegrate after sometime so their PDs were not stable.

Inception Voltage= 4 kV and PD pattern was recorded at 4.5 kV

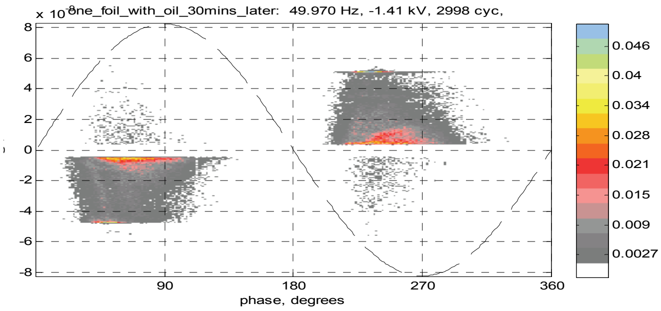

Figure 6.20 PD pattern recorded after 30 minutes for one foil test model in oil filled tube

From Figure 6.20 it is clear that the PD pattern is substantial symmetrical. The pattern is a combination of surface discharges from foil and gas bubbles in solid insulation as the gas bubbles in oil disintegrated.

6.6.2 Partial discharge measurement on scale down test model with two foils

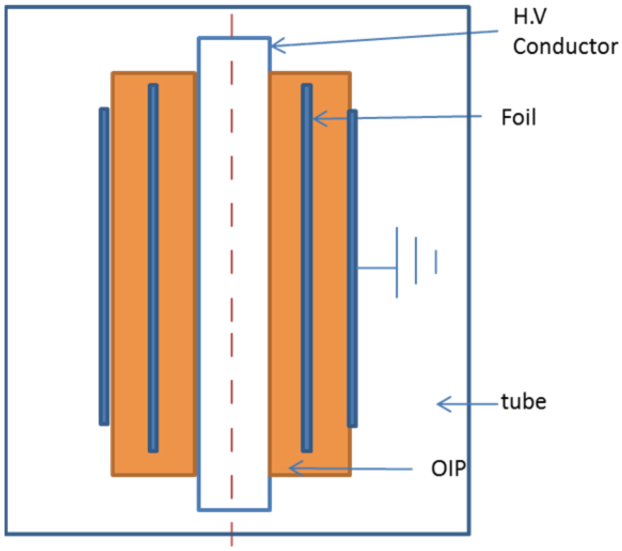

Figure 6.21 Schematic diagram of two foils test model

The papers were wrapped after first foil until the second foil was wrapped at calculated radial distance and it was shorter than the first foil in order to have capacitive radial grading in test model. The inception voltage and PD pattern was recorded without oil.

Inception voltage= 4 kV and PD pattern was recorded at 4.8 kV

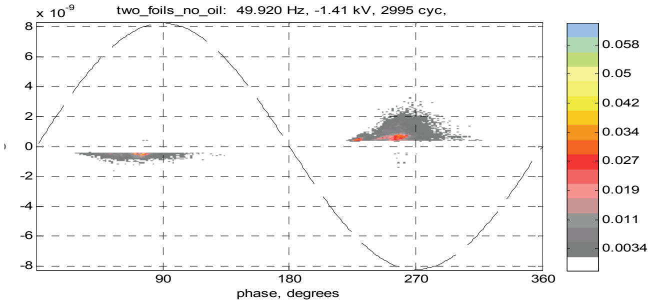

Figure 6.22 PD pattern for two foils test model without oil in tube

In two foils test model the papers were more pressed but still there were voids between the papers. From Figure 6.22 it is shown that the PD pattern is combination of voids and corona in air.

PD inception voltage and PD pattern was recorded on ICM system after filling the tube with oil.

Inception Voltage= 7.5 kV and PD pattern was recorded at 8 kV

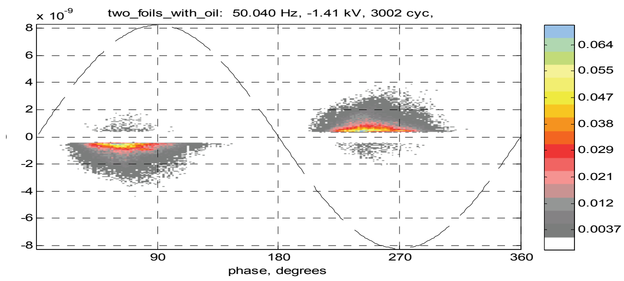

Figure 6.23 PD pattern for two foils test model with oil in tube

From Figure 6.23 it is clear that the partial discharge pattern is a combination of surface discharges from foils and gas bubbles in insulation. The PD pattern occurs between zero crossings and peaks of both half cycles. There is also an overshoot in both polarities. This type of discharge is dangerous to insulation. It is not possible to differentiate between the PD pattern from bubbles in oil and bubbles in solid insulation as both PD patterns are similar and it is difficult to remove bubbles from solid insulation that is oil impregnated papers [19]. In industry vacuum pump is used to remove bubbles from bushing but in laboratory it is difficult as the size of test model is still large as compared to a degassing chamber.

6.6.3 Partial discharge measurement on scale down test model with three foils

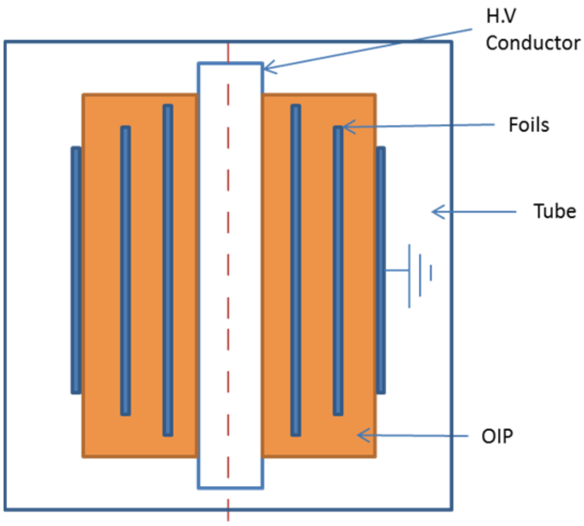

Figure 6.24 Schematic diagram of three foils test model

For the three foils test model the inception voltage was measured and PD was recorded without oil in tube. Third foil was earthed by using conducting wire and copper tape and it was not covered with papers.

Inception voltage= 5 kV and PD was recorded at 6 kV

Inception voltage was lower as compared to first test setup the reason could be that the inception voltage depends on a location of defect.

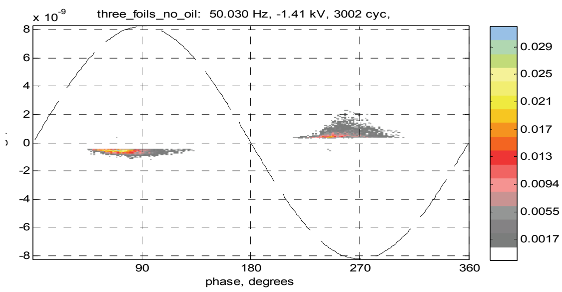

Figure 6.25 PD pattern for three foils test model without oil in tube

From Figure 6.25 it is clear that the PD pattern is the combination of corona and voids.

After inserting oil in tube, measurements were taken

Inception voltage= 8 kV and PD was recorded at 9.6 kV.

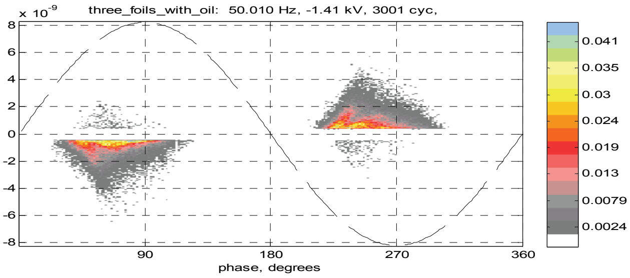

Figure 6.26 PD pattern for three foils test model in oil filled tube

From Figure 6.26 it can be said that the pattern is a combination of surface discharges from the foil edges and gas filled cavities as the pattern is substantial symmetric in both polarities.

Table 6.1 Inception voltage after each foil without oil in tube

Number of foils	Inception Voltage, kV
1	2.5
2	4
3	5

Table 6.2 Inception voltage after each foil with oil in tube

Number of foils	Inception Voltage, kV
1	4
2	7.5
3	8

Note:

- Corona in air can occur in both polarities depending on sharp point location. If the sharp point is in high voltage part then corona in air occurs in negative half cycle and if sharp point is on earthed foil then corona occurs in positive half cycle [10].
- Because of coupling capacitance the PD pattern is shown in opposite polarity as the direction of current is reversed.
- Regular partial discharge behavior in OIP bushing is ascending and descending with voltage signal cycle and it is because of cavities on papers layers as it is not possible to perform perfect impregnation and wrapping in lab manually [6].
- The reason for PDs with opposite polarities in case of voids is explained in section 3.3.3.2.
- The phenomenon of gas absorption or generation is called gassing. In gas absorption liquid PDs will disappear whereas in gas generation liquid more PDs will produce until the insulation breakdown. The gassing tendency of a liquid depends not only on the nature of liquid but it also depends on many experimental parameters e.g. an applied voltage, applied voltage duration, temperature, geometry of test setup etc. [25]. When geometry was placed vertically the gas bubbles were less but still the pattern is same as it is not possible to remove the gas bubbles from papers surface.

- During wrapping once tape was used to tight the paper but during experiment the corona was occurring at lower voltage 5 kV even with an oil in tube. The tape was creating problem because the dielectric strength of a tape is low therefore it breakdown at higher voltage.

6.7 Creation of defects in OIP bushing three foils test model

6.7.1 Defective third foil

The surface of third foil was damaged by making small holes in it.

Inception voltage= 8 kV and PD was recorded at 10 kV.

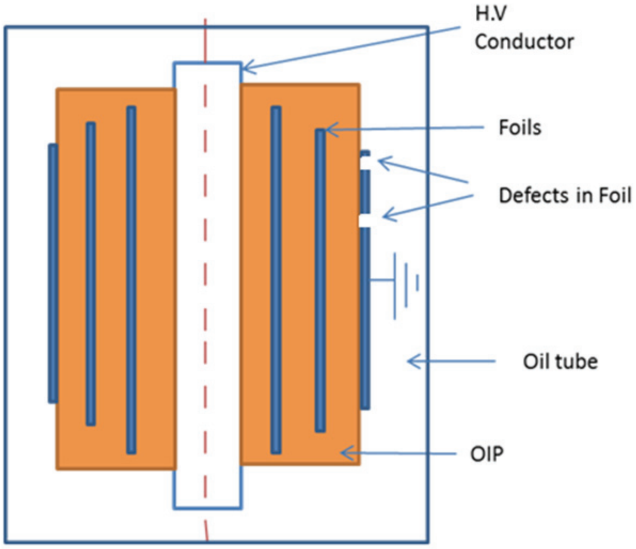

Figure 6.27 Schematic diagram for test model with defective third foil

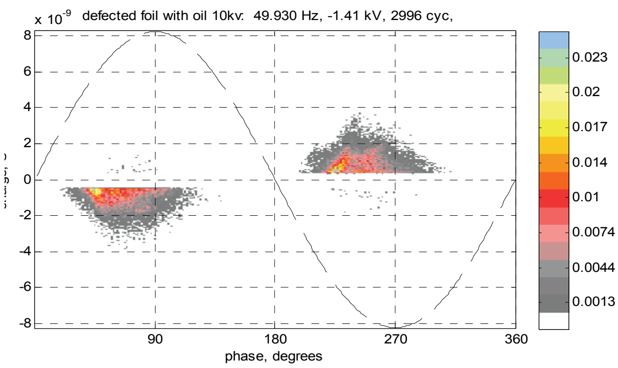

Figure 6.28 PD pattern for test model with defective third foil in oil filled tube

These defects did not create any difference because the tube was filled with oil and the damaged part was covered with oil. The PD pattern is the combination of surface discharges in oil and gas bubbles in insulation.

6.7.2 Addition of aluminium particles

The aluminium particles were added on the second foil and then again the papers were wrapped on it. The ´scaled down model was placed inside the tube without oil.

Inception voltage= 4 kV and PD pattern was recorded at 5 kV.

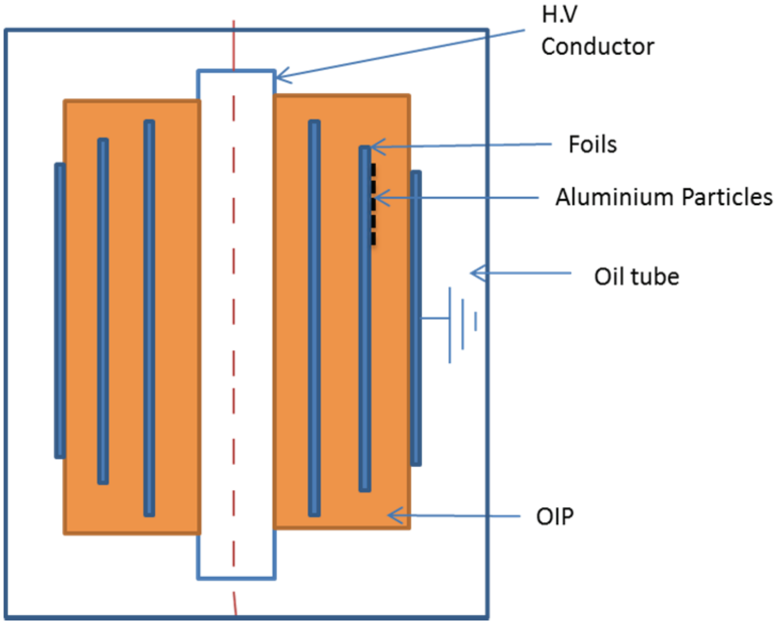

Figure 6.29 Addition of aluminium particles on second foil of bushing scale down model

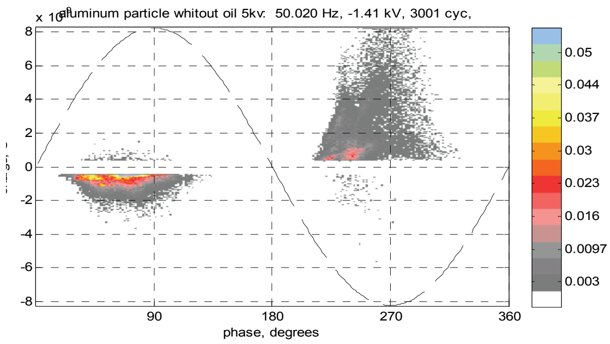

Figure 6.30 PD pattern for test model with aluminium particles on second foil and no oil in tube

The PD pattern is the combination of voids and corona as shown in Figure 6.30. In negative half cycle pattern is larger as corona in air occurs in negative polarity.

The tube was filled with oil and the measurements were performed.

Inception Voltage= 6 kV and partial discharge was recorded at 10 kV

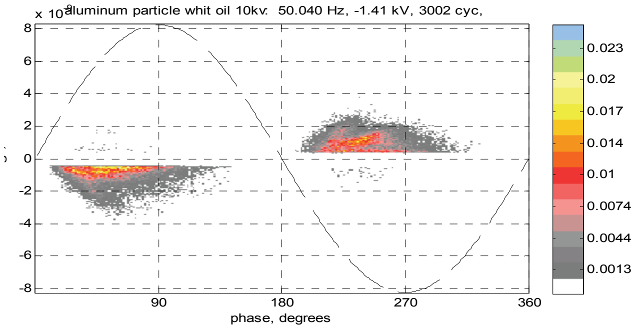

Figure 6.31 PD pattern with aluminium particles on second foil and oil in tube

From Figure 6.31 it is clear that the PD pattern is same as without aluminium particles because aluminium particles were not in contact with foil, they could be floating in oil.

When the aluminium particles were spread beneath the third foil. The inception voltage was 6 kV. The saturation was occurring in a PD recording therefore calibration was done again for scaling. Because of the aluminium particles there were sparks on foils and those sparks saturated the PD recording by amplifying it.

Note:

- In the oil impregnated insulations, particles in insulation can move to high electric field region. So the discharges may start even in discharge free insulations because of the moving particles [10].

7 Conclusions

- The 145 kV oil impregnated paper (OIP) bushing model is designed by using capacitive radial grading and the model is proposed in Comsol Multiphysics (CMPH) in order to analyze the electric field stresses and voltage distributions between foils. The voltage is almost uniformly distributed between foils and radial electric field stress is under the desired limitations.
- The scaled down OIP bushing model is designed by using a capacitive grading technique and the scaled down model is proposed in CMPH. The scaled down 5 kV model has almost the same electric stress as in a full scale model and the voltage is uniformly distributed between the foils.
- The scaled down model was manufactured in laboratory by wrapping impregnated papers and aluminium foils on conductor tube and the model was placed in oil tube. The papers were impregnated in the laboratory. It was not possible to avoid voids between layers of papers as the scale down model was manufactured in the laboratory.
- The partial discharge (PD) measurements were performed on scaled down model in the laboratory using insulation condition monitoring system. The defects were created in a scaled down model of bushing, but only sources of PDs in a scaled down model were most likely surface discharges from foil edges, gas bubbles and gas filled voids. It is difficult to differentiate between the pattern of gas bubbles on the solid surface and free gas bubbles from oil in tube.
- The aluminium particles and a defective foil do not have any large effect on the PD pattern. The aluminium particles created corona discharges in oil when they were in contact with foil and the defects in foils were covered by oil so they did not change the PD pattern.
- The laboratory measurement results verify the theoretical results in literature, as the main causes of partial discharge in OIP test models were gas bubbles and surface discharges from foils edges. When tube was not filled with oil the corona occurred from foil edges but with an oil in tube, corona occurred at high voltages so scaled down model results are applicable to practical 145 kV OIP bushing and these results can be used to analyze the signature of partial discharge in OIP bushings.

8 Recommendation for future Work

8.1 PD measurements performed on OIP bushing scaled down setup at different temperatures

Sometimes the bushings are subjected to thermal overload and the effect of the thermal overload regarding partial discharge activity is very important aspect of bushing. It is required to investigate the temperature dependence of PD activity in OIP bushing, using different temperature values above 105 °C which is the hot spot temperature of bushing. Temperature has significant impact on the gas bubbles. It is very important to investigate whether the gas bubbles extinguish at high temperature or more gas bubbles are generated that can lead to more partial discharges. By using a scaled down model it is possible to investigate the temperature effect.

8.2 PD measurements for transient overvoltage condition

In this thesis the PD measurements were performed at steady state voltage but practically bushings have to withstand switching surges and over voltages. It is very important to analyze the effect of transient voltages on PD behavior because in case of steady state voltage the PD pattern is continuous but for transient voltage pattern will be different. It is possible to perform measurements on scale down model of bushing by generating transient voltages in laboratory.

8.3 Partial discharge measurements on 145 kV OIP aged bushing

The PD measurements were performed on scale down model of bushing and the PD patterns are analyzed, but it is very important to perform measurements on practical 145 kV OIP aged bushing in order to compare PD patterns in scale down bushing and practical bushing from industry.

9 References

[1] S.V. Kulkarni, S.A. Khaparde, *Transformer Engineering Design and Practice.* 2004, Marcel Dekker, Inc.

[2] S.Rao, M.E, M.I.E, *Power Transformer and Special Transformer (Principle and Practice.* Third Edition, Second Reprint 2004

[3] G. Engdahl, H. Edin and R. Eriksson, *Electrotechnical Modeling and Design.* KTH, 2006.

[4] Dieter König, Y. Narayana Rao *Partial Discharges in Electrical Power Apparatus*. Vde-verlag gmbh, Berlin and Offenbach, 1993: pp. 15-26, 106-108

[5] M.Pomplili, C.Mazzetti and R.Bartnikas, "PD behavior in Switching Surge Aged Oil Paper Capacitor Bushing Insulation." *IEEE Transactions on Dielectric and Electrical Insulation*, Volume.9, No.1, February 2002.

[6] F.Colla, M.Pomplili, C.Mazzetti, "Partial Discharge Behavior of Oil Impregnated Paper Bushings." *IEEE International Symposium on Electrical Insulation*, 1998

[7] Comsol Multiphysics website http://www.comsol.com, last accessed 10-03-2011

[8] Power Diagnostix Systems GmbH, Bruesseler Ring 95a, 52074, Aachen, Germany, (www.power- diagnostix.com last accessed 26-09-2011.

[9] James H. Harlow, Loren B. Wagenaar, *Electric Power Transformer Engineering*. Chapter 12 Electrical Bushings, Second Edition CRC press 2007.

[10] T.J.Gallagher, A.J.Pearmain, *High Voltage Measurement Testing and Design.* John Willey and Sons, 1983 pp: 163-189.

[11] KTH Electrical Engineering Electrotechnical Design (EI2440) Project Task *High Voltage Bushing Design*. January 2010.

[12] J.S. Graham, *High Voltage Engineering and Testing*. Chapter 12 High Voltage bushings, Second Edition, IEE Power and Energy Series.

[13] Dieter Kind, Hermann Kärner, *High Voltage Insulation Technology*. Translated by Narayana Rao, pp. 120-125

[14] IEEE Std.C57.19.01-2000, "IEEE, Standard Performance Characteristics and Dimensions for Outdoor Power Apparatus Bushings. IEEE, 2000.

[15] IEEE Std.C57.19.03-1996, "IEEE, Standard Requirements, Terminology and Test Procedures for Bushing for DC Applications." IEEE, 1996.

[16] IEEE Std.C57. 19.00-1991 (R1997), "ANSI/IEEE, Standard Performance Characteristics and Test Procedure for Outdoor Power Apparatus Bushings." IEEE, 1997.

[17] IEEE Std. C57.19.100-1995 (R 1997), "IEEE, Guide for Application of Power Apparatus Bushings." IEEE, 1997.

[18] IEC. 137, "Bushings for Alternating Voltages above 1000 V." IEC, Geneva, 1995.

[19] ABB Transformer bushings, type GOE and GOE2 Technical guide "http://www.abb.se/product/db0003db004283/c12573e700330462c1256f5c004a7dbc.aspx." last accessed 05-03-2011.

[20] IEEE Std. 4-1995, "Standard Techniques for High Voltage Testing." IEEE,1995.

[21] http://www.powerinsulator.com/showproduct.asp?id=71 last accessed 18-08-2011.

[22] M.S. Naidu, V. Kamaraju, *High Voltage Engineering.* Fourth Edition, McGraw Hill Companies, 2009

[23] E.Kuffel, W.S.Zaengl, *High Voltage Engineering Fundamentals.* Pergamon press, 1984: pp. 371,250-252

[24] Dieter König, Y. Narayana Rao, *Partial discharge in Electrical Power Apparatus* Ch. 4 Effects of Partial Discharges on Electrical Insulating Materials by Prof. Dr. K. Moller and Dr. D. Maurer, vde-verlag gmbh, Berlin and Offenbach, 1993:pp.78-93

[25] P.Bezborodko, O.Lesiant and R.Tobazeon, "Study of Partial Discharge and gassing phenomenon within Gaseous in Insulating Liquids." *IEEE transactions on Electrical Insulations*, Vol. 27 No. 2, April 1992.

[26]www.abb.ca/product/db0003db004283/c12573e700330462c1256f5c004a7dbc.aspx?tabkey=7, last accessed,10-03-2011.

[27] J.V.Champion, S.J. Dodd, "Inter-foil Electrical Breakdown in High Voltage RIP Condenser Bushings." *IEEE 7th International Conference on Solid Dielectrics*, 2001 June 25-29, 2001.

[28] Cecilia Forssen, KTH Electrical Engineering Sweden, and High Voltage Engineering *Laboratory Experiment: Partial Discharge Measurement Technique.*

[29] Jitka Fuhr, "PD Source Localization in the Insulating System of Power Transformer" *IEEE, International Symposium on Electrical Insulation*, 2006.

[30] Nathaniel Taylor, *Dielectric Response and PD measurements on Stator Insulations at varied Low Frequency*. Doctoral Thesis, KTH, 2010

[31] M.Ghaffarian Niasar, H.Edin, X. Wang and R.Clemence "Partial discharge characteristics due to air and water vapour bubbles in oil." *International Symposium on High Voltage Engineering*, 2011.