ELEN 4003: HIGH VOLTAGE EGINEERING LABORATARY EXERCISE 2017

AUTHOR: RONEWA MABODI (598527) **LAB PARTNER: JOHANNES SENOAMADI**
LAB DEMONSTRATOR (U50): S. SITOLE **LAB DEMONSTRATOR (PD): A. MARASCHINI**
DATE: 21 APRIL2017

School of Electrical & Information Engineering, University of the Witwatersrand, Private Bag 3, 2050, Johannesburg, South Africa

Abstract: This paper presents the discussion of the laboratory results which is performed on the rod-plane configuration, sphere- sphere configuration and Partial Discharges. The predicted breakdown voltage is 265 kV and 281 kV for the rod-plane, and sphere- sphere configuration respectively at an air gap of 18.25 cm using FEMM. The experimented results show that the breakdown voltage is 123 kV and 294 kV rod-plane, and sphere- sphere configuration respectively using the U50 test method. The unknown device A is found to be at the center whereas the unknown device B is at the top. Both the positive and negative corona was observed on the Oguro needle setup. The inception voltage for negative corona is lower than that of the positive corona. The difference between the occurrences of the inception and extinction voltage are discussed. Future recommendation includes the use of a clean and smooth sphere to improve the accuracy of the results.

Key Words: Breakdown**,** Corona**,** Electric field, Insulation, Partial Discharge, Safety.

1. INTRODUCTION

Electric field generated by High Voltages (HV) displays various characteristics which are influenced by the geometry of the surrounding structure, the environmental conditions and the dielectric properties of these materials. The HV engineering investigates these influential parameters on various devices with the objective to design, test and to analyses different insulators [1]. Different insulators are used in industries and the choices of these insulators are based on the applications, the electrical properties, physical or economic properties of the device [2]. Degradation of insulation is one of the challenges which is faced in industries [3]. These degradations happen when insulating material fails to withstand the high voltages which is applied [1]. The core to these problem is the presence of impurities in the insulating material. Two most commonly used insulating materials include air and oil [4]. The breakdown of air is at 2.6 kV/mm [3]

Two laboratory experiments were performed and they will be they will be discussed in report. The first laboratory exercise was aimed to determine the breakdown voltage on the compulsory setup of the sphere- sphere and the chosen setup which is rod-plane. The second laboratory exercise was focused on determining the position of the two unknown which are immense in the oil and to investigate the partial discharges in air gaps with the aid of the Oguro needle.

Requirements: It is required that the practical laboratory experiment of the air breakdown has to be conducted in the HV laboratory. The first part of the experiments includes the determination of air breakdown between the sphere- sphere setup and the rod-plane setup. The second part of the laboratory exercise include the identification of the location of the unknown devices and to investigate the partial discharges in air gaps with the aid of the Oguro needle.The results obtained from the laboratory experiment has to be analyzed and discussed.

Assumptions: It is assumed that the temperature, humidity and pressure remain constant during the laboratory experiment. The altitude at the Witwatersrand is assumed to be exactly 1744 *m* above sea level.

2. CONTEXTUALISATION OF RELAVENT LITERATURE

In the presence of high voltages, the proximity of electrical devices may result in unfavorable effects such as change in operation and possible damage to surrounding devices. These effects can result in a form of corona, flashovers, or breakdown. As a result, this necessitates the need to perform tests on the insulators in order to warrant that they are capable of withstanding unexpected high voltages.

The breakdown of the material happens when the insulation material fails to withstand the electric stress [5]. This breakdown phenomenon occurs when the discharge bridges insulation and consequently lowers the potential differences between the electrodes to be zero [6]. As a result, short circuit is experienced during the occurrence of this phenomenon. Studies made in [7, 9] do shows that the breakdown of air is affected by the temperature, humidity and temperature.

2.1. Breakdown mechanisms

There two breakdown mechanisms are discussed. This mechanism include the streamer mechanism and the Townsend mechanism

2.1.1. The streamer mechanism

Steamer are said to be the channels of the breakdown ions which is called the plasma and their presence indicates the occurrence of short circuit [7]. This mechanism was generated by Raether and meek in 1940 [8]. Studies in [8] state that in this mechanism, the avalanches growth weakens when the charges concentrations ranges from 10^6 to 10^8. The breaking time in this mechanism ranges from 1ns to 100ns [7-8]. The streamer breakdown is based on three conditions.

- It is required that there should be 10^8 electrons for the satisfaction of this criterion.
- The electric field resulted from the space charge has to be equal to the background electric field.

$$\int_{x=0}^{x=d} a * dx = \int_{x=0}^{x=d} (a-n) * dx \approx 18-20 \quad (1)$$

The streamer propagates to the opposite electrode with speed which ranges from 0.1 m/us to 10m/us. The streamer can only reach the opposite electrode if the voltage which is applies is satisfactory to sustain the propagation process. The speed of the streamer is dependent on the voltage applied. The clearance path connecting the electrodes ranges from 2 cm to 200 cm [7]. When the number on the electrons exceeds the value of 10^8, the corona transfigures to be breakdown [7].

The electric for the above mentioned conditions is given used equation two below and it is obtained to be the summation of electric field due to the voltages across the space charge and the background electric field. The space charge electric field is denoted by the E_S ES and the background electric field is denoted by E_O

$$E_{tot} = E_o + E_S \quad (2)$$

2.1.2. The Townsend mechanism

This mechanism was discovered by J.S. Townsend in 1987 [7].The breakdown time of the Townsend mechanism is longer than that of the streamer mechanism In this mechanism, the increase in the voltage between the electrodes in gasses having electron attachment leads to the increase in current. This process occurs to the point whereby the dark current transits to the self-sustaining discharge. The dark current flow is determined by equation three below. Where I_o denotes the dark current, d is the air gap, I is the new current and γ is the Townsend insanitation constant.

$$I = I_o * \frac{e^{ad}}{1-\gamma*(e^{ad}-1)} \quad (3)$$

Uniform electric which occurs in small air gaps are the distinguishing features of this mechanism [7]. The pressure is low and this result to the low spark-over voltages [7]. In this mechanism the electrons accelerate from the cathode to anode in the presence of the electric field [5]. During photoemission, the accelerating electrons emits the photons before they collide with the anode [5]. This is because they have much energy. During the collision with the anode, positive ions are attracted to the cathode. As a result, the secondary electrons are emitted during the collision between the positive ions and the cathode. This process until breakdown phenomenon occurs when the generated secondary electrons are equal or greater than the initial number of electrons [5]. The discharge is capable of continuing with the presence of the source producing the dark electrons and this is known as the self-sustain [7]. When these conditions are met, the Townsends breakdown criteria is therefore satisfied. This process is characterised by$\gamma * (e^{ad}-1)$. The number of the secondary electrons is detriminded using equation four.

$N = N_o * \gamma * (e^{ad} - 1) \geq 2$ (4)

2.1.3. The Comparison between the two breakdown mechanism.

Table 1: Townsend and streamer mechanism

Townsend mechanism	Streamer mechanism
Low temperature	High temperatures
Low spark voltage	High Spark voltage
Breakdown time(us)	Breakdown time(ns)

3. LAB 1: U_{50} EXPERIMENT

This laboratory experiment was aimed on determining the breakdown voltage of gap between the two electrodes using the U_{50} method. The air gap between the two electrodes is 18.25 cm.

3.1. Experimental procedure

Before the laboratory can commence, a checklist on the safety measures is done. This includes making sure that the lab coat is worn without opened shoes. The other safety measure was to check if the all the equipment's are equipped with the earth stick. Safety questions were also asked by the demonstrator to see if the students understood. The test setup for the experiment is prepared before the laboratory experiment commences. The distance between the electrodes is measure and adjusted with the aid of the tape measure. As a result, a precision error of 2mm is assumed based on the following:

- The sphere electrode are not smooth
- Human error may results

The test circuit consists of a variac, transformer, the diode in forward bias, the Marx generator, the bleeding resistor, capacitor, resistor, spheres, potential divider and the oscilloscope. The testing circuit is shown in Figure 1A.

The variac is used to change the transformer turns ratio. The transformer of 220:140 000 is used to step up the voltage. The diode used has a resistance of 6.12Ω and it is rated (5kV Vrms,20 mA). The Marx generators are configured in five steps maintaining the V-shape. The bleeding resistor is used it has no resistance. The setup to be tested is connected in parallel with the bleeding resistor. There are two grounds so that the voltage can disperse quickly. A flat copper is for ground to reduce the inductance of the circuit. The bleeding resistor and the capacitor shape the voltage to produce the impulse. A potential divider is connected to the oscilloscope to measure the voltage and to concurrently offer a discharge path. The oscilloscope is connected to visualize the output voltage.

U50 Up down test procedure: The initial voltage is selected [7]. The initial voltage is chosen to a value which is closer to the projected flashover value. Thereafter, equally spaced voltage levels are selected. These voltage values are within the margins of the expected flashover values. When this is done, a first short may then be applied at the initial value chosen. If breakdown occurs, the next short will be applied at the value which is at the initial value minus the change in the voltage levels [7]. If, however breakdowns do not occur, the next short will be applied at the value which is at the initial value plus the change in the voltage levels. The results were taken using the digital oscilloscope. The values obtained were multiplied by ratio of 157453 to obtain the voltage in kV. When there is the occurrence of a breakdown or withstand, the voltage is either decreased or increased by decreasing or increasing the gap between the spheres of the first stage. The rotation of was fixed at quarter of the sphere which consequently which changes the voltages.

For the first setup which is the sphere to sphere, the initial voltage is selected to be 260kV as predicted from the simulations as shown in the prelab. Several tests were done and the breakdown was not reached. The voltage couldn't be increased since the charge voltage was approaching 80 kV. The demonstrator then suggested that the gap should be decreased to10 cm.

3.2. Experimental results

Sphere- sphere configuration: The fixed rotation at quarter of the sphere changed the voltage by kV (uniform voltage level of U50). The initial breakdown is at 103.93 kV.

Table A1 in Appendix A shows the output voltage, the charge voltage and the resultant breakdown state. The results obtained shows that the number of breakdown is 12, while the number of withstands is 10. The results are graphically shown in Figure below.

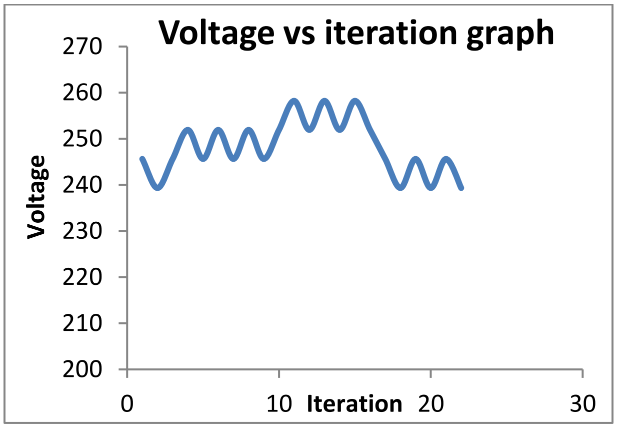

Figure 1: Sphere- sphere output voltage vs. iteration

The fixed rotation at quarter of the sphere changed the voltage by kV(uniform voltage level of U50). The initial breakdown is at 103.93 kV.

Rod-Plane configuration

A table showing the output voltage, the charge voltage and the resultant breakdown state is shown if table A2. The results obtained shows that the number of breakdown is 12, while the number of withstands is 11. The results are graphically shown in Figure two below.

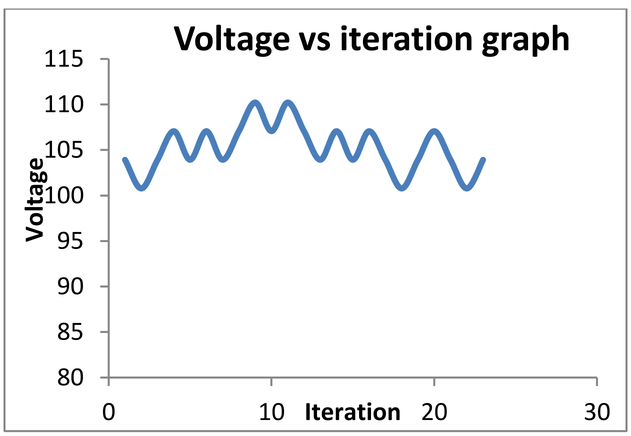

Figure 2: Sphere- sphere output voltage vs. iteration

4. CORRECTION FACTORS

Tables 2: Variables definitions and constants[20]

Variable	symbol	Value
Air density correction	7	
Humidity correction	K2	
Corrected disruptive voltage	U0	
Disruptive voltage	U	
minimum path discharge length	L	
Pressure in laboratory	P	0.08374 bar
Standard pressure	P0	0.1013bar
Temperature in laboratory	T	21◦C
Standard temperature	t0	20◦C
Absolute humidity	ho	11g/m^3
Relative humidity	R	31%

Air density correction[20]:

$$\delta = \frac{P}{P0} \times \frac{273+to}{273+t} \tag{5}$$

$$\delta = \frac{0.08374}{0.1013} \times \frac{273+20}{273+21}$$

$$\delta = 0.8238$$

$$k1 = \delta^{m} \tag{6}$$

$k1 = 0.8238^{1}$ =0.8238

This correction is considered reliable since it is within 0.8 and 1.05.

Finding exponents[20]:

$$g = \frac{U50}{500L\delta k} \tag{7}$$

Humidity correction[20]:

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

h=5.34 g/m^3

Since humidity is greater than 2, the variable m and w are 1 and 0 respectively.

The ratio $\frac{h}{\delta}=\frac{5.34}{0.8238}$ =6.43

k= 1+0.010($\frac{h}{\delta} - 11$)

k= 0.9537

$k2 = \text{ k}^{w}$ (9)

$k2 = \ 0.9537^{0}$

K2=1

Atmospheric correction factor for gaps [20]:

$Kt = k1 * k2$ (10)

Kt =0.8238*1

Kt =0.8238

Corrected Disruptive Voltage [20]

For both the sphere- sphere and rod-plane, n_b>n_w.

***Sphere- sphere**:*

Table 3: Sphere- sphere withstands and breakdown

I	Voltage	n_b	n_w
3	258.22	3	0
2	251.92	4	3
1	245.63	4	4
0	239.33	1	3
		12	10

k=10

ΔV=6.3 kV

Vo =233.03 kV

V50=Vo+ΔV [$\frac{A}{N} + \frac{1}{2}$] (11)

A=$\sum_{i=0}^{k} in_{iw}$ (12)

=0*3+1*4+2*3+3*0=10

N=$\sum_{i=0}^{k} n_{iw}$ (13)

=3+4+3+0=10

V50=242.48 kV

$U0 = \frac{U}{Kt}$ (14)

$U0$ =294.34 kV

Error = 17.6 %

***Rod-plane**:*

Table 4: Sphere- sphere withstands and breakdown

I	Voltage	n_b	n_w
3	110.22	2	0
2	107.07	6	2
1	103.92	4	5
0	100.77	0	4
		12	11

K=11

ΔV=3.92 kV

Vo=96.08 kV

V50=Vo+ΔV [$\frac{A}{N} + \frac{1}{2}$]

A=$\sum_{i=0}^{k} in_{iw}$ (15)

=0*4+1*5+2*3+3*0=11

N=$\sum_{i=0}^{k} n_{iw}$ ()

=4+5+2+0=11

V50=101.96 kV

$U0 = \frac{U}{Kt}$ (16)

$U0$=123.78 kV

Error = 17.6 %

4.1. Analyses of the results

Breakdown voltage comparison: The breakdown voltages for the two setups are different. The breakdown voltage of the sphere- sphere voltage is found at an average value of 294.48 kV while the breakdown of the rod-plane has an average breakdown voltage of 123.78 kV. The reason for the difference in breakdown voltage of the two setups is that they have different radius of curvatures. The electric field strength is different and hence the voltage required to ionise air is different.

The Rod– Plane setup has a higher radius of curvature when compared to the Sphere- sphere setup. Electric fields are concentrated at the sharp point of the rod, this make it easier for air to be conductive or to breakdown, hence causing the breakdown to occur at a lower voltage. In the sphere- sphere setup, the electric fields are spread out and much more non-uniform and hence resulting to the required breakdown voltage to be higher.

The error on the measured results is found to be 17.6 %

Factors affecting the results: The three environmental conditions affecting the results and the other factors are listed below.

- The temperature before the start of the experiment is at 21℃ and it is 20℃ after the experiment. The decrease in temperature results in the increase breakdown voltage. Because the air become less dense.
- Relative humidity is 31 % at the start and it is 26 % at the end of the experiment. The decrease in humidity results in the decreases breakdown voltage.
- Atmospheric pressure is 0.8374 Bar. At the start of the experiment and it 0.8357 Bar at the end of the experiment. The decrease in pressure results in the decrease in breakdown voltage.
- The spheres where not smooth and they were dirty. This affected the length of the gap to be measured.
- Human errors also resulted when measuring the gap length.
- The capacitor is not fully discharged after a shot/ iteration
- There is no sufficient retrieval time for the ionized air to diffuse.

The expected breakdown voltage for the Sphere-sphere configuration was 281kV whilst the expected breakdown voltage for the rod plane setup was 265 kV. This is the prediction at the air gap of 18.25 cm. This was simulated using FEMM and the results are on the submitted prelab.

4.2. *Approximation of multistage by the single by single stage generator:*

The multistage generator can be approximated in the single stage generator. Figure two shows the single stage approximation of the Marx generator used in the lab.

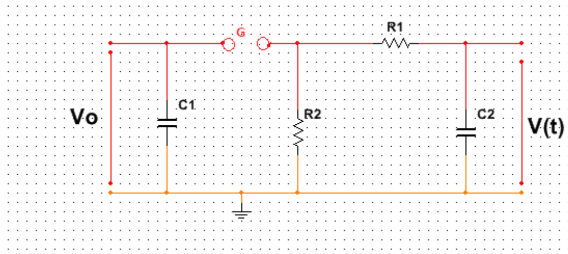

Figure 3: Equivalent model of a Marx generator [7]

4.3. *Alternative ways to perform U50 test*

The alternative ways to perform the U50 are the Multi-level method and the Extended up and down method [7]. In the Multi-level method test voltages are chosen. Then a pre-specified number of shots is applied at each level and the number of breakdowns are counted at each level. The results can be obtained by drawing a line of best fit on the graph of Probability vs Voltage [7]. The method is efficient since it does not assume normality of distribution. It is criticized for time consuming. The Extended up and down method determines the discharge voltages that corresponds the probabilities. If the applied impulse does not result in a discharge, the voltage is increase by uniform steps until breakdown occurs, and then the voltage will be decreased. This method is better that theU50 Up down test in that the IEC switching withstands voltages are defined as ten percent withstands [7]. The discharges on the test object are at a value closer to ten percent of the impulse unlike at U50 Up down which is at 50 percent [7].

5. PARTIAL DISCHARGE MEASUREMENTS

The Partial Discharge laboratory experiment aimed on investigating the PD in the polyethylene material and to also detects the defects in the insulator so that corona may be caught before it causes damage. This test are important and they are usually done in the devices which are newly introduced and in most cases they are used for insulating materials to be used in transmission lines[15]

Various factors are known for the development of the corona activities. Some of these include the contaminants in the materials, the manufacturing faults and the voids formed in the material as caused by the physical contortion. The challenges with the discharges are that they weaken the insulating material which consequently leads to treeing [15]. Persistence of PD will consequently leads to the irreversible breakdown of the insulating material.

5.1. Partial discharge test procedure

The laboratory experiment is conducted in an environment where the charge is 0.1pC and the frequency of 50 Hz which is the frequency at the national grid. The cause of having a charge is because of the fact that there are light bulbs and the effects from the environment [1, 3]. The safety induction is done before the lab can be performed. The calibration is done in order to make sure that the results will not be affected by noise. The calibration is done by injecting 5-10 pC to the partial discharge machine [21].

The machine used is the ICM compact and the source is the Variac. The following steps are therefore used to setup the test device. Step one include removing the electrodes and then disconnecting the ground from the test object. We then connect the ground and connect the electrode.

After the above procedure, the test object was then immersed into the oil so that the test may not affected by the surrounding environment. This is maintained by the fact that oil has a higher breakdown voltage as compared to the surrounding air [7]. The voltage was then increased by the experimenter from 0 V at 1kV up until maximum 10kV is reached. The increase is done every 30 seconds until the 10 kV. When the voltage reach 10 kV, the experiment was paused for two minutes and then the voltage slowly decreased to 0 V. When this is done the inception voltage, the extinction voltage, and the sound were taken into consideration.

Reason for pausing after the experiment: The test equipment was grounded every time after the experiment with the purpose of making sure that each experiment is independent from the other. Grounding enables the test equipment to fully discharge.

5.2. Definitions

Inception Voltage (IV): This is the voltage wherein the applied voltage causes the initiation of partial discharges or the voltage wherein the discharges attain exceeds the specified low voltage [1, 11]

Extinction Voltage (EV): This is the voltage wherein the specified voltage level are reduced to the value whereby the discharges are lower than the specified voltage [1, 11].

Trichel pulses: These are pulsed that occur as a results of negative corona. These pulses are dense charges [11-13].

Residual charges: These are the charges that result in the magnitude of the PDIV and PDEV to be different [11, 16-17].

5.3. IEC 60270 PD test circuit.

The IEC 60270 PD test circuit contains of the current limiting resistor, a detection impedance, and the coupling capacitor. The coupling capacitor can either be used as a testing device or a filter. The testing circuit also includes PD measurement equipment, the test object and it is capable of obtaining readings from the circuit for display. The test object has a capacitor which can be charged and discharged. At a point of discharge, both the charges and voltage drops from Q=CV and this happen so fast in nanoseconds.

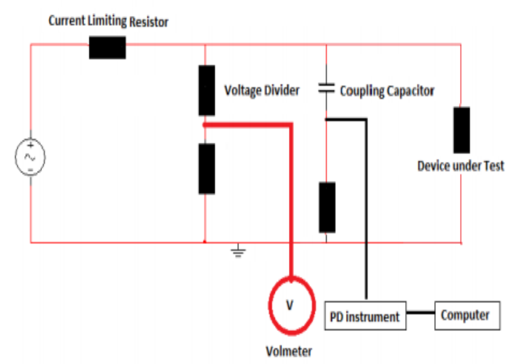

Figure 4: IEC 60270 PD test circuit [21]

5.4. Unknown device one

Figure five to seven shows the screen short of the results obtain during test for the first unknown device. Figure B1 in Appendix B shows the charges due to noise and they are found to be 0.14pC at 0.0 kV.

Inception Voltage: Figure five shows the PDIV which is found to be 3.78 kV.

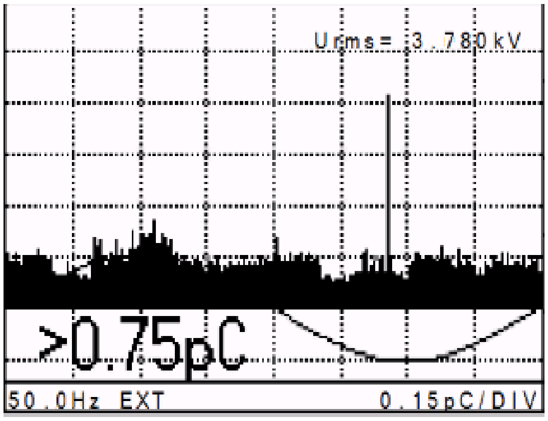

Figure 5: Unknown device one Inception voltage.

Table 5: Selected results of Partial Discharge.

Qp Mean [pC]	**U_{rms} [kV]**	**$U_p/\sqrt{2}$ [kV]**
0,54	3,78	3,85
0,68	3,77	3,85
0,32	3,79	3,88
0,34	3,85	3,94
0,75	3,93	4,02
0,65	3,96	4,06

It can be seen from the table that when the voltage is increased, the resultant Qp mean increases steadily. The corresponding plots are shown in appendix B.

Extinction Voltage: Figure six shows the PDEV which is found to be 4.53 kV. The resultant plots of charge, voltage against time are shown in appendix B.

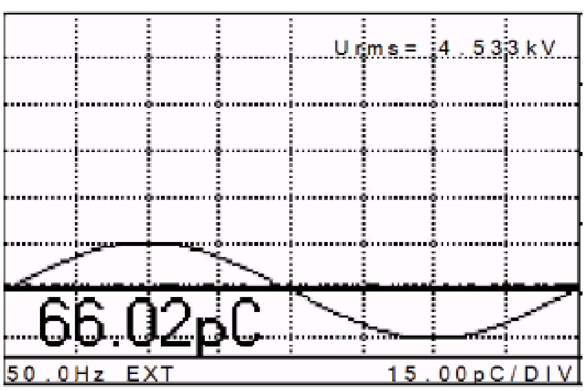

Figure 6: Extinction voltage

Location prediction: The Partial discharge in figure seven shows the magnitude which is almost equal in magnitude in both half circles.

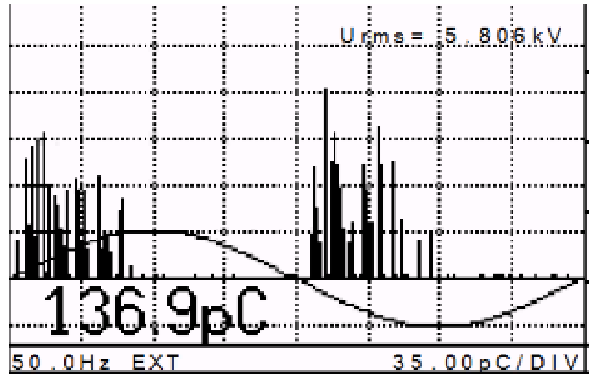

Figure 7: Partial discharge of unknown device one.

The results to this equality in half circles is shows that they have the same defects in the air-cavity. The density of the charge and the magnitude of the charges are evaluated to predict the position of air cavity. Looking at the screen shot provided in the figure above, it can be seen that electrons are moving from the insulator wall to the other in both the half circles. The inception voltage is 5.8 kV which is between 5 and 10 kV [15]. With the provided FEMM simulation in the prelab, this clearly shows that the cavity is at the center. The PDIV make sense in that the process of ionization has to occur in the insulator first and it requires high voltage [7].

5.5. Unknown device two

Figure eight shows the screen short of the results obtain during test for the second unknown device. Figure C1 shows the charges due to noise and they are found to be 0.14pC at 0.0 kV. PDIV which is found to be 4.29 kV. The corresponding plots are shown in appendix C. The resultant plots of charge, voltage against time are shown in appendix C.

Location prediction: The Partial discharge in Figure eight shows the magnitude which is higher on the positive half circle. The same pattern is observed as the voltage is increased and it can therefore be concluded that unknown device two is located at the top (closer to the positive electrode). This matches the simulation in device B for the prelab exercise.

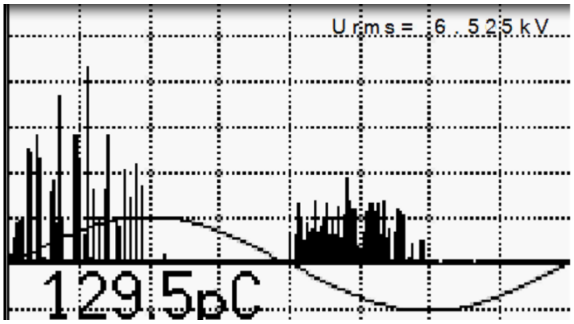

Figure 8: Partial discharge of unknown device two.

5.6. Oguro needle

This laboratory experiment is aimed to investigate the partial discharges in air gaps with the aid of the Oguro needle. The needle is sharp and the test are performed on it since it induces breakdown. The figure below shows the experimental setup. This setup is similar to that or the rod-plane.

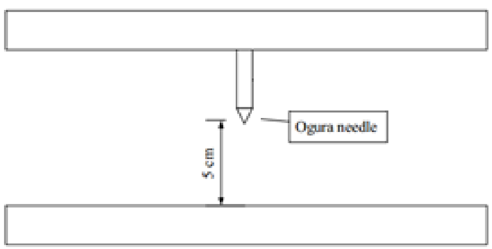

Figure 9: Oguro needle setup.

Experimental results and discussion: The results obtained for the inception and extinction voltages for both the positive and negative corona are shown in Figure 10 to 13.

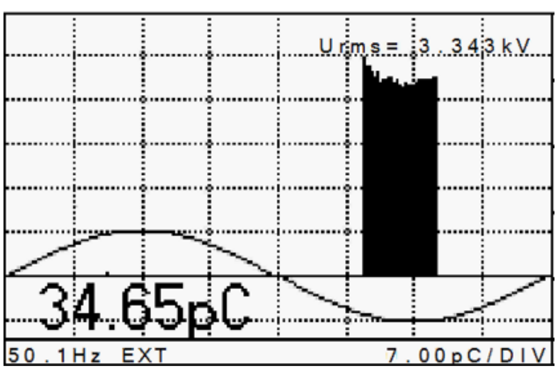

Figure 10 :Negative corona inception

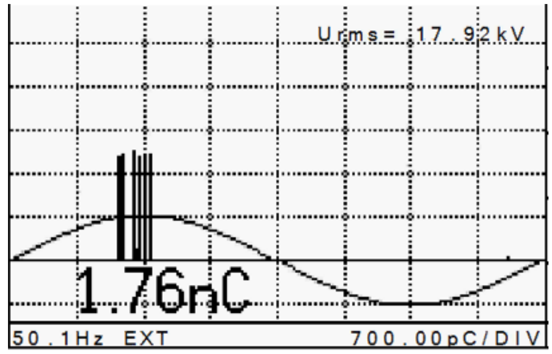

Figure 11: Positive corona inception

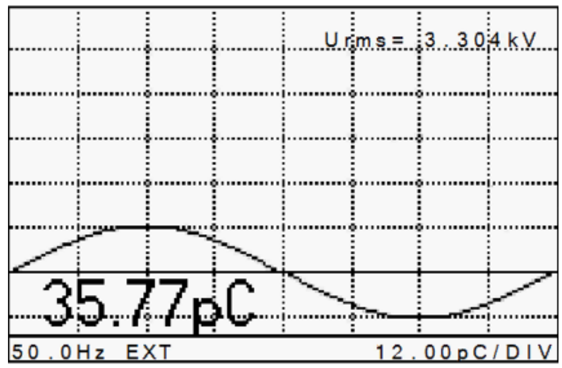

Figure 12: Negative corona extinction

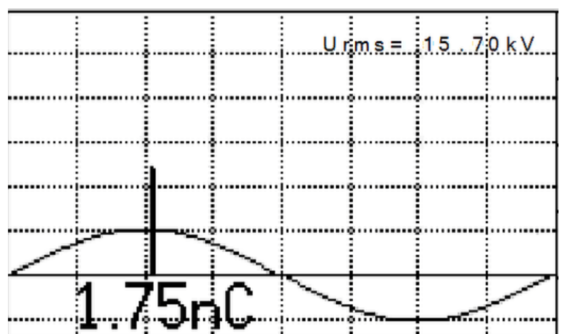

Figure 13: Positive corona extinction

The inception voltage for the positive corona is 17.92 kV which is way higher when compared to the inception voltage of the negative corona which is 3.43 kV. The Width for the negative corona pulses is observed to be wider than that of the positive corona. This is due to the fact that the number of free electrons in the negative corona is higher as compared to the number of free electron in the positive corona. This makes sense considering that there less voltage will be required for ionisation [18]. The other major observation is that as the voltage was increased, the pulses for the negative corona were becoming wider and the magnitude was reducing. This shows that the electrons in the negative corona do not have more energy, so when the voltage increases, it actually increase the collision between the electrons which consequently lead to the loss in energy. The similar observation is made for the extinction of the negative corona.

The graph on charge, voltage and time are shown in appendix D. Table six shows the relationship between charge, and voltage at values closer to negative corona inception. The results show a rise in charge at the voltage of 3.34 kV which is the point of negative corona inception.

Table 6: Selected data on Oguro needle.

Qp Mean [pC]	U_{rms} [kV]	$U_p/\sqrt{2}$ [kV]
0.25	3.32	3.43
0.24	3.33	3.48
0.28	3.33	3.49
34.23	3.34	3.52
0.25	3.41	3.56
0.29	3.40	3.57
0.31	3.40	3.56
0.29	3.40	3.55

5.7. General discussion and answers to questions

Identification of devices: The inception voltage is expected to be between 5kV and 8 kV for the cavity at the centre and less than 3kV for the cavity situated at the top [15]. Based on the measured results which are presented on screen shots, the results confirm that the first cavity for unknown device one is at the centre while the cavity for device two is at the top. This also makes sense and it confirms simulation for device A and B which was performed in the prelab.

Factors that affected the results: Poly might be degraded and aging. The oil used during the laboratory experiment appears to have other materials or dirt. The precision of increasing the voltage can also affect the point where the expected results of PDIV and PDEV are expected.

Reason why inception is lower than extinction voltage: From the results obtained from the Oguro, the inception voltage for the negative corona is 3.34 kV and the extinction voltage for the negative corona is 3.304 kV. The main factor is that the residual charges which are stored do not get discharged immediately. The remaining charge therefore affects the results, and as a result we can see that the inception and extinction voltages are not the same. The PDIV is the voltage across the sample wherein the PD activity occurs. Whereas the PDEV is the highest voltage wherein the continuous corona of pulse specified amplitude do not occurs as the input voltage is steadily reduced from the PDIV. So, as the corona begins, the voltage is decreased which therefore leads to the extinction voltage being lower.

Reason why inception voltage for negative corona is lower than that of positive corona and/or why the negative inception voltage occurs early: The reason behind this concept is due to the fact that the initiatory electrons in the negative corona occurs in a region with high electric field (the sharp point of the needle). This is different from the initiation of electron in the positive corona which originates in a volume of which is found to be small at low voltages [14]. So as the voltage was increased during the laboratory, the volume was also increased together with the increase in the detachment coefficient which there contributed to huge number of initiatory electrons. A critical observation is that the negative corona is dependent on the point electrode which is the Oguro needle and this is not surprising since the initiatory electrons develop at the electrode surface.

The cause of random spikes: These spikes are caused by the bubbles which are inside the oil.

Why do we avoid pointing and creating sharp points in the lab: Based on the results observed on the Oguro needle experiment, it is concluded that the electric field are concentrated at the sharp point. This therefore increase the electric field strength at a sharp point since the radius of curvature is small. So pointing in an HV laboratory which is charged may lead to the formation of an arch which can lead to electric shock and cause severe injuries and even death.

Causes of PD due to physical processes: The main issues that result to PD are; the presence of contaminants in the material, the voids which is made in the material due to physical distortions and also the chemical reactions occurring and heating.

Manufacturing faults on the material may also lead to PD.

Corona discharge: This is the partial discharge which occur as a results of the localised gaseous breakdown and it is due to ionisation [19]

Cavity discharge: This is the localised dielectric breakdown in an empty space of a material during high voltage stress [19].

Colour of the corona: Initially the energy level of the positive ion is greater than that of neutral molecules. As the voltage is increasing, a free electron referred to quanta is captured and it is therefore emitted from the molecule. . This free electron is radiated in a form of EM wave And it appear in visible light range (between 620–585 nm) when exposed to molecules such as nitrogen and oxygen. As a results we see an orange color since it is within that range.

If device E in figure 4 is used and there is partial discharges, what could be the possible cause: The cause contributing to the Partial discharge in this set up may be due to the availability of moisture and also we should also consider that that the material used is not ideal.

Other comments: It is observed that the occurrence of PD is stimulated by overstressing of the gaseous occlusion and discontinuities in the insulator. The magnitude the pulse of the PD resembles the amount of energy that it is dissipating on the insulator

6. RECOMMENDATIONS

It is recommended that the spheres should be made as smooth as possible so that they do not have effect on the experimental results. The oil to be used should not have dirt and bubbles since they have an effect on the results. It is vital that the aging of the oil is known so that assumptions can be made on how much effect it can have on the results.

7. CONCLUSION

The laboratory experiment is composed of two parts. The first part required the determination of the electric breakdown strength of an air-gap. The second part of the experiment was aimed on the evaluation of the performance of insulation devices. The breakdown voltage for the rod-plane and the sphere- sphere setup is found to be 123 kV and 294 kV respectively. The accuracy in the experimental results has been verified and it has been compared with those listed in the IEC standards. The error in the measured results is computed to be 17.6 %. The unknown device A is predicted to be at the center whereas unknown device B is on top. The reason causing the negative corona to occur early is due to the fact that the initiatory electrons in the negative corona occurs in a region with high electric field(the sharp point of the needle).

REFERENCES

[1] K. Wang, Y. Liao, L. Wang, Study of DC corona inception and extinction voltage measurements on electrode surface using UV corona monitor. IEEE,2007, China.

[2] A.T. Wilder, R. Hebner, Y. Wang, Surface finish effects of partial discharge with embedded electrodes, IEEE, 2003, USA.

[3] B. Kanchanapalli, M. Valavala, Measurement of air breakdown voltage using standard gap method. Journal of Electrical Engineering, p1 – 6.

[4] L.W. Van Veen, Comparison for partial discharge measurement in power cable, 2014.

[5] Nyamupangedengu. Electric breakdown mechanisms in gases, University of the Witwatersrand , 2017,S.A.

[6] R. TObazeon, Prebreakdown phenomena indielctric liquids,IEEE,1994.

[7] E.Kuffel, W.S. Zaengl, J.Kuffel, High Voltage Engineering. Fundamentals Butterworth, Heinemann, 2nd ed,2000,U.S.A.

[8] H. Raetha, electron avalenches and breakdown in gases, Butterworth, 1964, London.

[9] M. G. Hogg, I. V. Timoshkin, S. J. Macgregor, M. P. Wilson, M.J.Given, T.Wang, Electrical breakdown of short nonuniform airgaps, IEEEP, ,2013, USA.

[10] C62.82.1-2010, IEEE Standard for Insulation Coordination--Definitions, Principles, and Rules, *IEEE*, pp. 1-22, April 2011.

[11] IEC Standard. High-voltage test techniques: partial discharge measurements. *IEC-60270*, 2000.

[12] P. Sattari, G.S.P Castle, Numerical simulations of Trichel pulses in a negative corona discharge in air.2010.

[13] M. Cernak, The first Trichel pulse of negative corona discharge in N2 with a small admixture of sf6. 1989, Japan.

[14] G.G. Raju, Dielectrics in electric fields, 2nd ed.,CRC press.2003, Canada.

[15] C. Nyamupangedengu. PD-type-dependent spectral bandwidth in solid polymer dielectrics. PhD thesis, 2011. S.A.
[16] K. Yukihiro I. Kuniharu, The characteristics of spread of residual charge in micro gap and PD break down,IEEE,2009,China.
[17] Y.V. Yurgelenas, M.A. Leeva, Development of a Barrier Discharge in Air in h ighly nonhomogeneous Electric Field caused by the Residual Dielectric Surface Charges, IEEE, 2009.
[18] Evan. Meyerhoff. Corona and its Effects, High Voltage Connection Inc., pp 1-4, 2007.
[19] Du, B.X. He, Z.Y. Du, Q. Guo, Y.G. Crossequipment study on charging phenomena of solid insulators in high voltage equipment, *IEEE*, Vol. 23, N. 1, pp 134 – 141, February 2016.
[20] IEC, International Standard. IEC 60060-1:2000 High-voltage test techniques, part 1 General definitions and test requirements, 3rd ed. 2001. Switzerland.
[21] IEC, International Standard. IEC 60270:2000 High-voltage test techniques-Partial discharge measurements. 3rd ed. 2001. Switzerland

APPENDIX A

Appendix A contains data for the U50 experiment

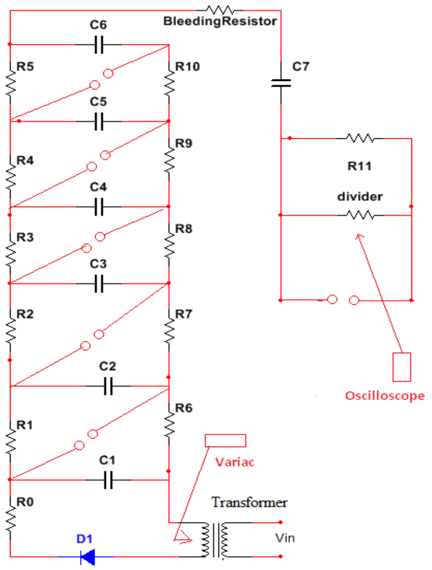

Figure1A: Experimental circuit

Table 1A: Sphere- sphere configuration data

Oscilloscope Voltage(V)	**Charge Voltage (kV)**	**Output Voltage (kV)**	**Condition**
1.56	25	245.63	B
1.52	24	239.33	W
1.56	23	245.63	W
1.60	25	251.92	B
1.56	20	245.63	W
1.60	24	251.92	B
1.56	22	245.63	W
1.60	24	251.92	B
1.56	26	245.63	W
1.60	23	251.92	W
1.64	24	258.22	B
1.60	25	251.92	W
1.64	23	258.22	B
1.60	25	251.92	W
1.64	24	258.22	B
1.60	24	251.92	B
1.56	23	245.63	B
1.52	22	239.33	W
1.56	23	245.63	B
1.52	24	239.33	W
1.56	23	245.63	B
1.52	21	239.33	B

Table 2A: Rod-plane configuration data

Oscilloscope Voltage (mV)	**Charge voltage**	**Output Voltage (kV)**	**Condition**
660	103.92	25	B
640	100.77	24	W
660	103.92	23	W
680	107.07	25	B
660	103.92	20	W
680	107.07	24	B
660	103.92	22	W
680	107.07	24	W
700	110.22	26	B
680	107.07	23	W
700	110.22	24	B
680	107.07	25	B
660	103.92	23	W
680	107.07	25	B
660	103.92	24	W
680	107.07	24	B
660	103.92	25	B
640	100.77	24	W
660	103.92	23	W
680	107.07	24	B
660	103.92	23	B
640	100.77	21	W
660	103.92	22	B

APPENDIX B

- Appendix B contains data for the unknown device one.

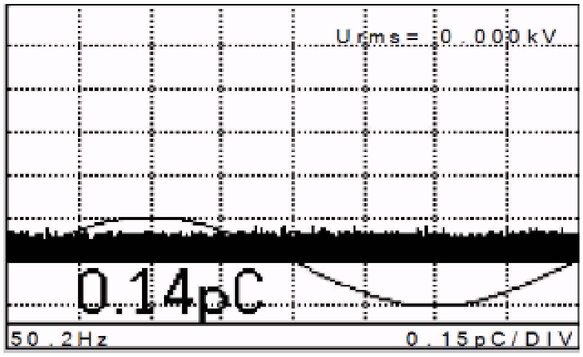

Figure 1B: Charges in in circuit due to noise

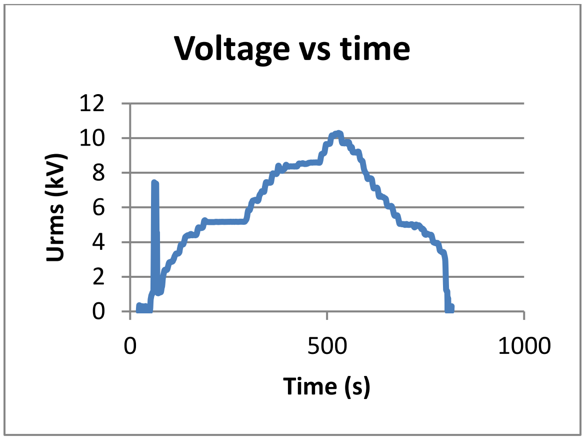

Figure 2B: Voltage vs. time graph

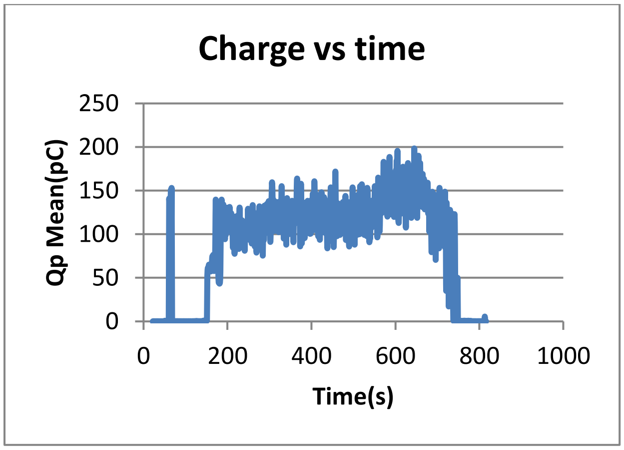

Figure 3B: Charge vs. time graph

APPENDIX C

Appendix C contains data for the unknown device two.

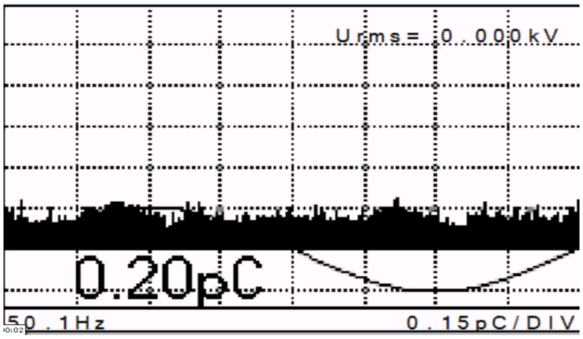

Figure 1C: Charges in in circuit due to noise

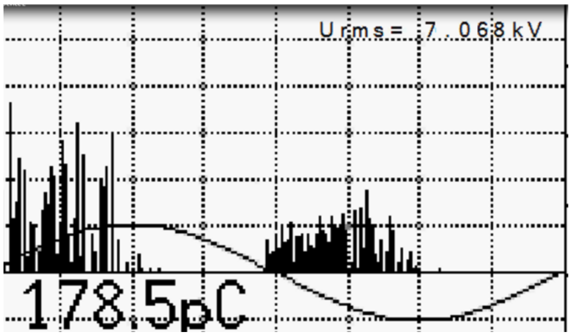

Figure 2C: Partial discharge of unknown device two

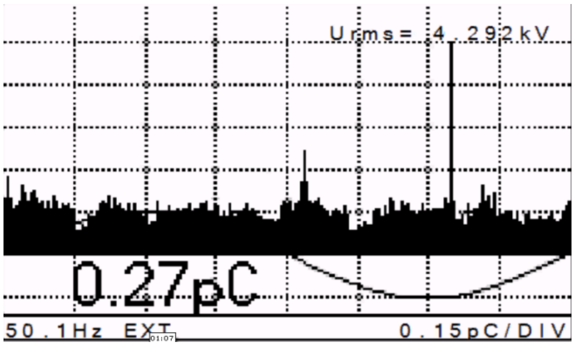

Figure 3C: Inception unknown device two

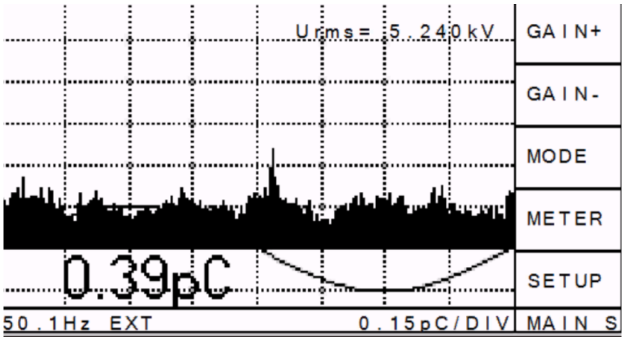

Figure 4C: Extinction voltage

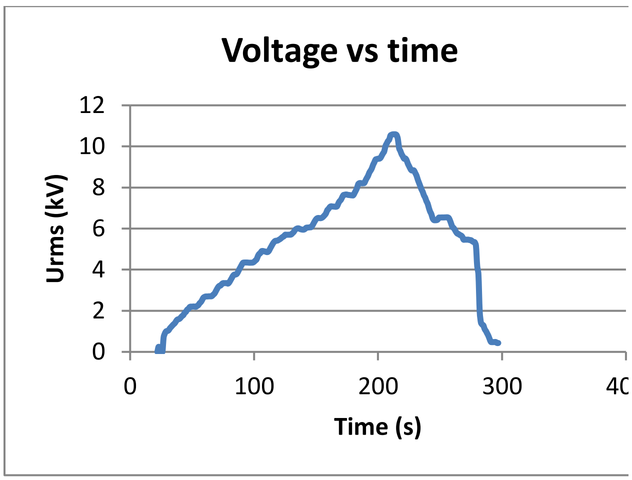

Figure 5C: Voltage vs. time graph

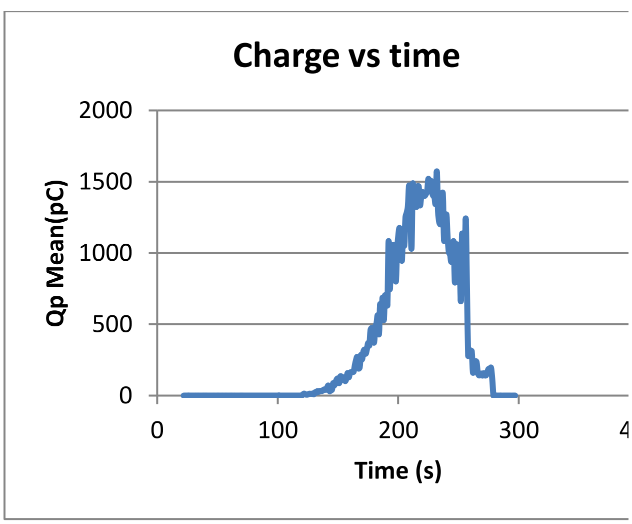

Figure 6C: Charge vs. time graph

APPENDIX D

Appendix D contains data for the Oguro needle

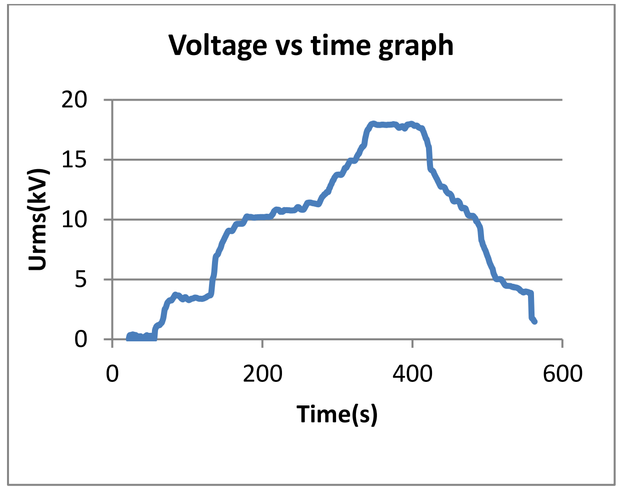

Figure 1D: Voltage vs. time graph

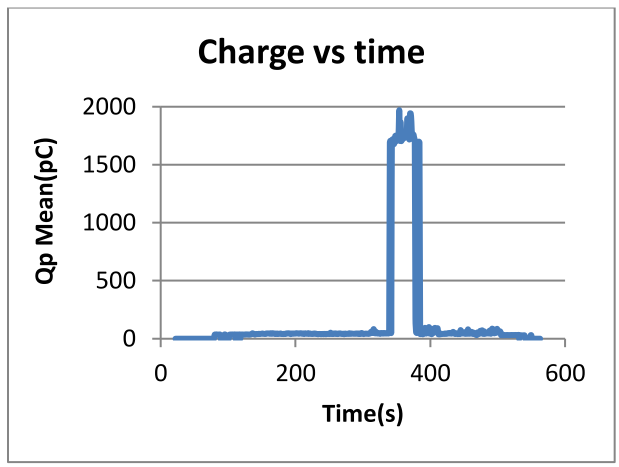

Figure 2D: Voltage vs. time graph

- The figure below shows the relationship between charge, voltage and time. This shown for voltage from 0 to 10 kV with varying time. The results show that the charges do increase as the voltage increase, although the increase is not linear. The blue plot shows the charge and the red plot shows the voltage.

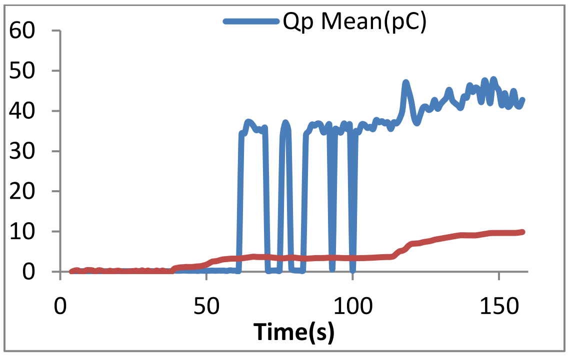

Figure 3D: Voltage vs. time graph

APPENDIX E

ELEN 4003- HIGH VOLTAGE ENGINEERING PRELAB REPORT

AUTHOR: RONEWA MABODI (598527) **LECTURE: CUTHBERT NYAMUPANGEDENGU**
LAB PARTNER: JOHANNES SENOAMADI **LAB DEMONSTRATOR: ALESSANDRA MARASCHIN**
DATE: 21 APRIL 2017

School of Electrical & Information Engineering, University of the Witwatersrand, Private Bag 3, 2050, Johannesburg, South Africa

Abstract: This paper presents the simulations, discussion and answers of the prelab questions in preparation of the laboratory experiment. The laboratory exercise is aimed to test and analyze the potential of electrical breakdown of insulation in cases when an insulating material fails to endure the electric field stress. Safety questions concerning the high voltage laboratory are answered to demonstrate the understanding for safety measures to be taken into consideration. The environmental factors affecting experiment are noted to be temperature, altitude above sea level, atmospheric pressure and humidity. The iterative method is used to predict the 50 % breakdown voltage of the rod-plane gap and the sphere-sphere gap. The breakdown voltage for the rod-rod gap setup is 265 kV. The results obtained in Partial Discharge simulations shows that the electric field is lower when the permittivity is high.

Key Words: Breakdown**,** Electric field, Insulation, Partial discharge, Safety

8. INTRODUCTION

The goal of this laboratory exercise is to investigate the electric breakdown characteristic of an insulation. The student is required to understand and to be able to demonstrate knowledge using the U50 up-down test to determine the breakdown voltages. The experimental setups and the electric profile are performed using FEMM software package [1]. The five different setups are simulated for the solid insulation to determine the electrical breakdown. The simulated results are discussed and analyzed based on the theoretical knowledge of electric field.

9. SAFETY

2.1 Answer to question one: Bearing in mind that the laboratory experiment is taking place in a high voltage laboratory where the operating currents are huge, the earth stick is used to produce a protective path for short circuit conditions. In general, these earth stick ensures that the sources are discharged.

2.2 Answer to question two: The basic principle of a capacitor is to store charges. This simply means that capacitors with high storage can store charges which can sufficiently cause injuries when it is not discharged. So having the capacitor bank's terminal shorted is a way to insure that the electric charges within the capacitors are always discharged.

2.3. Answer to question three: The use of current limiting resistance in the HV experiments is of paramount importance since they will aid in limiting the currents magnitude in the HV experiments during the events of failure and short circuit tests.

2. 4 Answer to question four: No, the pointing of objects in a high voltage laboratory is not advisable. When you point using a finger, the finger became a sharpest point. The electric field will result around the finger and it will be shunted to ground via the body.

10. LAB 1: U_{50} EXPERIMENT

3.1 Gap length determination:

Student 1: 598727, Student 2: 601073. The largest number combination is 73 from the last digits, therefore the gap length is obtained to be 18.25 as shown below.

$$d = \frac{73}{40} \text{ x } 10 = 18.25 \qquad (1)$$

3.2 Numerical Method to predict 50% breakdown

In this laboratory exercise the breakdown voltage of an air gap is determined by making of the basic method of iteration. This methodology is based on the streamer criteria. The starting voltage was chosen based on the results in the following experimental results performed at Wits [2]. The study suggest that the breakdown voltage is 81.2 kV for a gap of 20 cm. Having this results, linearity is assumed and the starting voltage is now calculated as:

$$V_{start} = \frac{V_b}{20} \text{x} 18.25 = 74 \text{ kV} \quad (2)$$

As a results the starting voltage is chosen to be 74 kV. FEMM simulations are performed on both the configurations (the rod-plane and Sphere-sphere setup) and the electric field profile is shown in Figures 1 to 4.

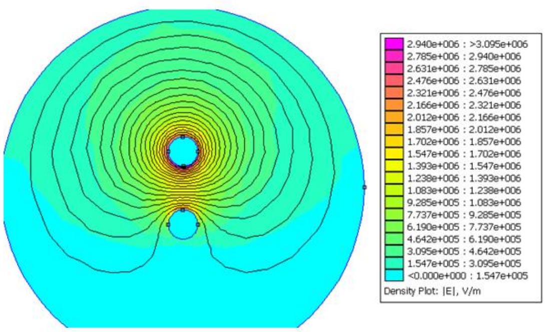

Figure 1: FEMM Sphere-Sphere setup and E -Field distribution.

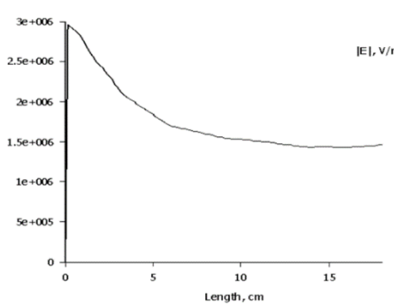

Figure 2: Sphere-Sphere Rod E-field Profile

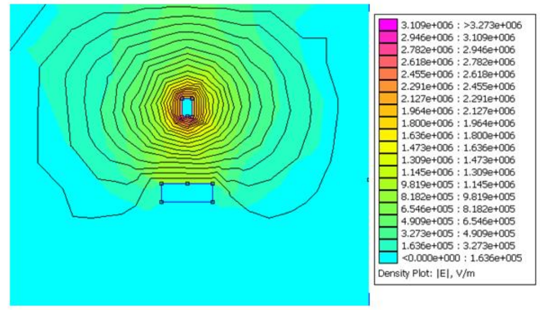

Figure 3: FEMM Rod-Rod setup and E-Field distribution.

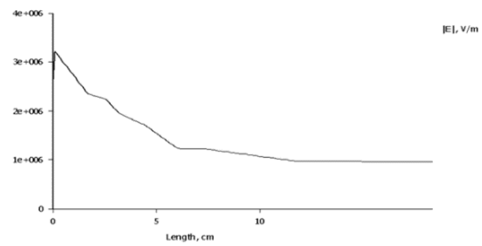

Figure 4: Rod-Rod E-field Profile

The segmented width for the electric filed plots is chosen to be 0.2 mm which allow possible shots of about 912 which is about 45 times larger than the recommended IEEE minimum shots of 20 and hence increasing precision [3]. The value for the average electric field was determined per shot from the point of highest electric field using the C++ program. Whilst making use of the iterative method, the simulations shows that breakdown occur when the voltage is 265 kV for the rod-plane setup and it is 281 kV for the sphere-sphere set-up. The atmospheric pressure (P) for Johannesburg is obtained using equation three below and it is obtained to be 0.82 bar.

$$P = 101325 \, (1-2.25577 * 10^{-5} * h)^{5.25588} \quad (3)$$

The altitude at the Witwatersrand is altitude (h) 1744 m above sea level. To determine K, equation for and five are used.

$$k_n = 1.605 * X[E_n - 2.165 * \text{P}]^2 - 0.2873P * X \quad (4)$$

$$K = \sum_1^n k_n \quad (5)$$

For $k_n > 0$, and 18≤K≤20

From the simulations, the value of K if found to be 18.214 for the sphere-sphere set-up at a voltage of 281 kV and K is found to be 18.117 for the rod-plane set-up at a voltage of 265 kV and they satisfy the streamer breakdown criteria.

3.3 U50 Up down test procedure: When using this method, the initial voltage is selected. This voltage is chosen to a value closer to the expected flashover value. Thereafter, the voltage levels which are equally spaced are selected. This values are within the margins of the expected flashover value [4]. When this is done, a first short may then be applied at the initial value chosen. If breakdown occurs, the next short will be applied at the value which is at the initial value minus the change in the voltage levels [5, 6]. If, however breakdowns do not occur, the next short will be applied at the value which is at the initial value plus the change in the voltage levels.

3.4 Alternative ways to perform U50 test: The alternative ways to perform the U50 are the Multi-level method and the Extended up and down method [3, 7]. In the Multi-level method test voltages are chosen. Then a pre-specified number of shots is applied at each level and the number of breakdowns are counted at each level. The results can be obtained by drawing a line of best fit on the graph of Probability vs Voltage [3]. The method is efficient since it does not assume normality of distribution. It is criticised for time consuming. The Extended up and down method determines the discharge voltages that corresponds the probabilities. If the applied impulse does not result in a discharge, the voltage is increase by uniform steps until breakdown occurs, and then the voltage will be decreased. This method is better that theU50 up down test in that the IEC switching withstands voltages are defined as ten percent withstands [3]. The discharges on the test object are at a value closer to ten percent of the impulse unlike at U50 up down which is at 50 percent [3].

3.5 Environmental conditions: The environmental conditions that may affect the experiment include Humidity, Temperature and atmospheric pressure, and the altitude above sea level. The breakdown voltage increases with a change in humidity. These changes can only increase the breakdown voltage by less than three percent when the absolute humidity change is between 8 and 15g/m3 [3]. The Johannesburg relative humidity is anticipated to be at 16% during the day of the experiment [8], which is different from the 50% RH which is assumed in the ambient conditions. However, for a gap which is 18.25 cm, the humidity effects on the breakdown voltage will be way lower than three percent [9, 10]. Some of the equations do assume ambient temperature of 20∘C and pressure of 101.3kPa [11]. The temperatures and pressure will be fluctuating during the experiment.

3.6 Test circuit: The figure five shows the Marx generator during the charging state. Marx generator circuit is a circuit type which is capable of generating high DC voltage from low DC supply source [13]. It has finite number of capacitors which are initially connected bin parallel on its charging state. During the discharge state, this capacitors are connected in series.

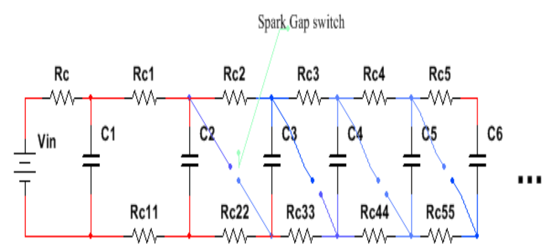

Figure 5: Marx generator circuit (charging) [13].

11. PARTIAL DISCHARGE MEASUREMENTS

Device A: It is important to first note that the permittivity of the insulator which is the polythene is higher than the permittivity of air. In this set-up the air gap is located at the center of the insulation. The electric field is uniform until the point where there is an air gap. At this point we expect a jump in electric field. The reason being that the electric field is low where there is high permittivity [14]. The electric field profile depicted in figure conforms to the expected results. The breakdown voltage is 3.8 kV.

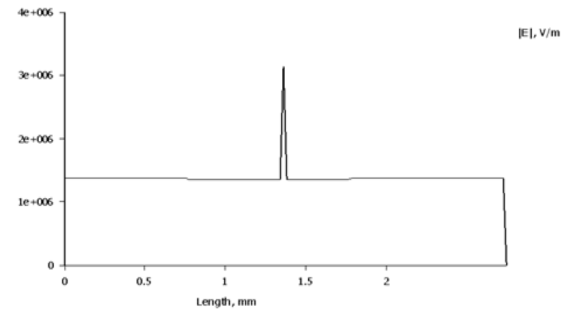

Figure 6: Device A E-filed profile

Device B: For the set-up depicted in device B, The electric field is expected to be enhanced in the first 36 µm where the gap is positioned. Therefore we expect a constant decay of electric field. The simulations conforms to the expectations. The breakdown voltage is 4 kV.

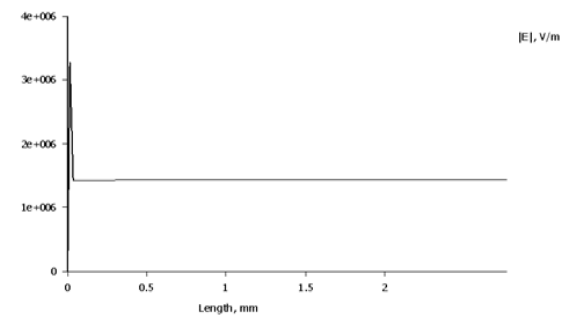

Figure 7: Device B E-filed profile

Device C: In this set-up, the electric field is expected to be higher in the last 36 µm of the gap height. This is because the air gap is located at the bottom and we expect to see a jump in electric field before reaching zero. The breakdown voltage is 4 kV.

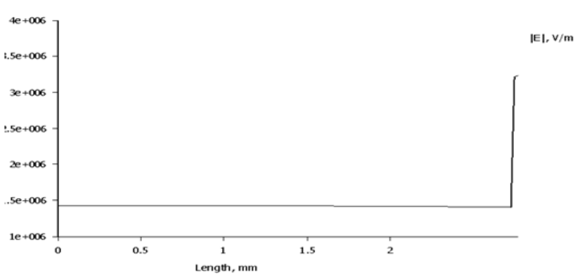

Figure 8: Device C E-filed profile

Device D: The electric field profile of this set-up is constant. Theoretically this makes sense since. This makes sense since the set-up is for the uniform field. The Electric fields around the parallel plates is expected to be constant. The breakdown voltage is 4.5 kV.

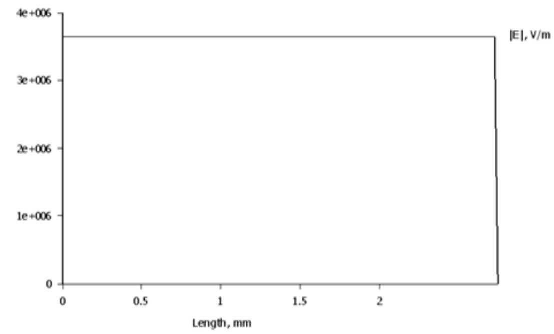

Figure 9: Device D E-filed profile

Device E: In the setup of the Oguro needle, the electric field is expected to be concentrated in the center where there is a sharp point of the needle since it has a small radius of curvature. The Oguro needle is set to have the length of 50 mm, and diameter of 5µm. The breakdown voltage is 4.5 kV.

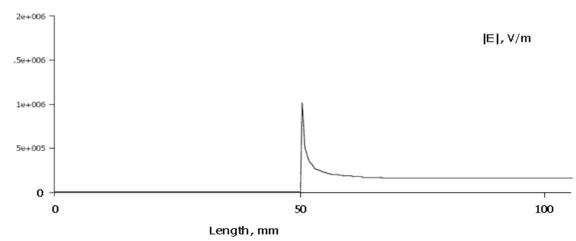

Figure 10: Device E E-filed profile

4.2 Definitions

Inception voltage: This is the voltage result to the initiation of partial discharges [17].
Extinction voltage: This is the voltage at which the effect of corona may be stopped. This voltage occurs as the voltage is decreased [17].
Trichel pulse: These are pulsed that occur as a results of negative corona.
Residual charge: These are the charges that makes the inception and extinction voltages to be different [15-16].

4.3 Partial discharge test circuit: The test circuit consists of the current limiting resistor, the detection impedance, and the coupling capacitor. The coupling capacitor can be used as a filter and a testing device. The circuit also comprises of the PD measurement equipment, the test object and it is capable of obtaining readings from the circuit for display. The test object has a capacitor which can be charged and discharged. At a point of discharge, both the charges and voltage drops from Q=CV and this happen so fast in nanoseconds.

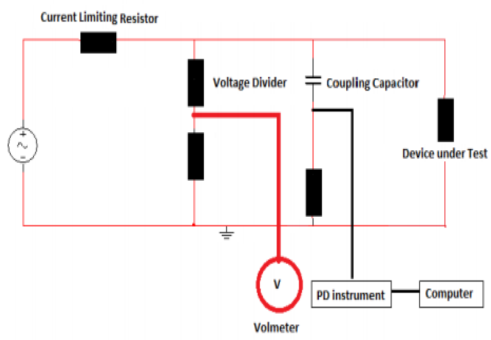

Figure 11: PD measurements test circuit[18]

Why do we avoid the creation of sharp: This is avoided since it results to the concentration of electric field at that certain point.

What physical process cause PD activity: Lightning ,insulations defects and the voids which is made in the material due to physical distortions

Corona: Corona can be defined a manifestation of luminous and audible discharge which are observed in the non-uniform fields before the occurrence of the breakdown phenomenon. Corona occurs when the voltage exceeds a certain value that result in gaseous ionization (breakdown of air) [17].

If device E in figure 4 is used, what can cause PD: The cause contributing to the Partial discharge in this set up may be due to moisture and also we should also consider that that the material is not ideal and there can be air particles?

12. CONCLUSION

This paper is aimed to presents answer of the prelab questions. FEMM simulations are performed to determine and demonstrate the breakdown voltages, and distribution of electric-field in different mediums. The simulated results were analyzed and discussed. The student understand the safety related issues which are to be taken into consideration during the laboratory experiment.

REFERENCES

[1] D. Meeker, *FEMM*. U.S.A: N.p., 2013. Print.

[2]T. Gora,Invetsigating the effects of altitude (air density) on HVDC breakdown voltage of smaller rod-plane air gaps,2016, S.A.

[3]E.Kuffel, W.S. Zaengl, J.Kuffel, HighVoltageEngineering. Fundamentals,Butterworth-Heinemann,2nd ed,2000,U.S.A.

[4]S. Vibholm, P. Thyregod, A Study of the Up-and-Down Method for non-Normal Distribution Functions, IEEE, Vol. 23 No. 3, 1988, Denmark.

[5]A. Beroual and J.H. Rakotonandrasana, Determining of U50 breakdown voltage for long air gaps submitted to negative switching voltage using a predicitive dynamic model. SAIEE, 2009, S.A.

[6]S. Vibholm and P. Thyregod, The Analysis of Insulation Breakdown Probabilities by the Up and Down Method, IEEE Trans., Vol. EI-21, no. 2, pp.133-136, 1986.

[7] S. Meijer, A. Girodet, J. J. Smit , Comparison of the Breakdown Strength of N2, CO2 and SF6 using the Extended Up-and-Down Method, IEEE, 2006

[8]South African weather service http://www.southafricanweather.co.za/aat/?Detailedweather=77105, south African weather, (Accessed 18 march 2017)

[9]L. I. Sirotinski, High Voltage Technique, Editura Energetica de Stat,1954

[10]The Institute of Electrical and Electronics Engineers, IEEE Standard Techniques for High Voltage Testing, The Institute ofElectricalandElectronicsEngineers,1978.

[11]M. G. Hogg, I.V. Timoshkin, S.J. Macgregor, M.P. Wilson, M.J.Given, T.Wang, Electricalbreakdownofshortnonuniformairgaps,"inProceedingsofthe19thIEEEPulsedPower Conference (PPC '13), pp. 1–4, San Francisco, 2013, USA.

[12]S. Flazi, M. Talhi, and H. Hadi, Factors affecting the breakdown of air gap between a discharge and ice-plane or wet-plane surfaces. In Eleventh Int. Conf. Atmospheric Icing of Structure (IWAS'05), 2005, Canada.

[13] W. J. Carey and J. R. Mayes, Marx generator design and performance, U.S.A

[14]C. Nyamupangedengu. PD Measurements (IEC60270), University of the Witwatersrand ,20 April 2017.

[15] K. Yukihiro I. Kuniharu, The characteristics of spread of residual charge in micro gap and PD break down, IEEE,2009, China.

[16]Y.V. Yurgelenas, M.A. Leeva, Development of a Barrier Discharge in Air in HighlyNonhomogeneous Electric Field Caused by the Residual Dielectric Surface Charges, IEEE, 2009.

[17] G.G. Raju, Dielectrics in electric fields, 2nd ed.,CRC press.2003, Canada.

[18]IEC Standard. High-voltage test techniques: partial discharge measurements. *IEC-60270*, 2000.

[19] IEC, International Standard. IEC 60060-1:2000 High-voltage test techniques, part 1 General definitions and test requirements, 3rd ed. 2001. Switzerland.