ELEN4003: HIGH VOLTAGE ENGINEERING LABORATORY REPORT

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<u>Abstract</u>: The aim of this documentation is to discuss and investigate the breakdown properties of insulators under different conditions. The laboratory experiment is separated into two parts. Part 1 is the U_{50}test, which is to determine the 50 % breakdown voltage of air gaps. In these experiments, 1.2/50 µs standard impulse voltage waveform is used on sphere-sphere and rod-plane electrode configurations and the air gap distance is 10 cm. The method used in this experiment to find the U_{50} voltage is the up and down method, the IEC 60060-1guide is used in this method. The report discusses the differences and similarities obtained from the analytical and experimental method. Part 2 is the Partial Discharge (PD) tests, which are used to investigate the effects of foreign objects in an insulator. In this experiment, a polyethylene sheet is subjected to a void of air. Different electric field profiles are used to determine the position of the void. The report contains comparative analysis between the simulated and the experiment results. Additionally, the Ogura needle results are analyzed.

Keywords: 50 % breakdown voltage, sphere-sphere, rod-plane, partial discharge, up and down method, ogura needle

1. INTRODUCTION

The advancement of technology and high voltage equipment such as Rotating machines results in the need for engineers to develop and understand insulating systems. The breakdown voltage of insulators is important for the design of high voltage electrical equipment as these insulators are used to protect the equipment [1]. In this experiment, the breakdown strength of air gaps under different conditions is investigated.

This document presents the results analysis for both U_{50} and PD tests. Additionally, the report contains the answers to questions presented in the lab brief [1].

2. BACKGROUND AND THEORY

The requirement of this laboratory exercise is to investigate the breakdown properties of air under different conditions. These conditions include the environmental factors such as temperature, humidity, and pressure. A reliable numerical method is required to predict the 50 % breakdown voltage of the sphere-sphere gap and rod-plane gap. Additionally, a comparative analysis between the numerical and experimental results is required.

In the PD test, FEM simulations for all the devices listed in the lab brief [1] are required. A reliable method of determining the inception voltage is required. Furthermore, the physical experiment results should be analyzed to determine the position of the void in the insulator.

This laboratory exercise will be deemed successful if all the requirements presented in the lab brief are met. These include answering all the questions and providing reliable methods to predict the PD inception voltage for all the devices and to predict the 50 % breakdown voltage for both sphere-sphere and rod-sphere configurations.

In high voltage engineering, it is important to understand the properties of insulation materials. The air in the atmosphere acts as an insulator between the positive and negative charges on the cloud and ground. When this insulator cannot withstand the charge subject to in, it breaks down and allows charge to travel from the cloud to the ground. This phenomenon is known as lightning. Lightning is of interest in high voltage engineering because the charge generated by lighting can cause fatal damages to electrical equipment. To analyze the properties of lightning, several methods are used. These methods include subjecting air under high voltage pulse and observing the voltage at which the air gap breaks. The gap is modeled using different electrode configurations like sphere-sphere, rod-plane, rod-rod, plane-plane, etc.

There are different statistical analyses used to analyze the breakdown voltage of air under certain conditions. Three general testing methods that have been accepted by IEC are:

- Multi-level method
- Up and down method
- Extended up and down method

These methods are presented in [2]. The methods are presented in the IEC 60060-1 as the disruptive – discharge test procedures [3]. In the up and down method, a starting voltage $\boldsymbol{V_i}$ is selected using appropriate methods. Then equally spaced voltage levels $\Delta\boldsymbol{V}$ below and above the initial voltage are determined. The first shot is applied at the initial voltage $\boldsymbol{V_i}$. If at this voltage there is a breakdown the next shot is applied at $\boldsymbol{V_i}$ - $\Delta\boldsymbol{V}$. If there is a withstand the next shot is applied at $\boldsymbol{V_i}$ +$\Delta\boldsymbol{V}$. The IEC 60060-1 recommends a minimum of n = 20 voltage application for self-restoring insulations to determine the 50 % breakdown voltage [2, 3].

Partial discharge is a localized electrical discharge or spark that partially bridges a small part of the insulation between two conductors [2, 3]. There is a certain amount of energy emitted by this process, the energy is in a form of electromagnetic emissions (i.e. light and heat), acoustic emissions (i.e. audible and ultrasonic ranges), and ozone and oxide of nitrogen gasses [4]. PD testing is important in predictive maintenance because it helps to ensure the reliability and longevity of electrical systems and equipment [5]. This testing is used to monitor the health of electrical systems in a facility to avoid insulation failure [5]. There are several testing solutions available to suit specific testing requirement [5].

- Offline PD testing
- Online PD testing
- Continuous PD monitoring
- Very Low Frequency (VLF) cable PD mapping

There are different types of partial discharges. These include the internal discharges, surface discharges, corona discharges, and treeing [6]. Internal discharges occur in voids or cavities within a liquid dielectric and corona discharges take place in the gaseous dielectric in the presence of inhomogeneous fields [6].

In this report, internal discharges and corona discharges are investigated. The corona discharges are investigated using an Ogura needle and internal discharges are investigated using polyethylene sheet subjected to a void of air.

3. PART ONE U_{50} EXPERIMENT

In this section, the up and down method used in the laboratory is discussed. Furthermore, the comparative analysis is provided, this analysis compares the results obtained in the numerical method and experimental. The results obtained from the numeral method include simulations, a reliable method used to determine the 50 % breakdown voltage. The numerical method results are presented in the prelab that is presented in appendix C.

3.1 Up and down method

The up and down method presented in the SANS 60060-1 is used in this experiment. This method is of the three methods approved by the IEC standard for determining the 50 % breakdown voltage of insulators. The aim is to determine the 50 % breakdown voltage of 182.5 ***cm*** gap, this was obtained using the student numbers of the experimenters, and the equation used is presented in appendix C. However, the gap was changed to be ***10 cm*** gap. This change was due to the environmental conditions in the laboratory. That being said the analysis presented in this report is for an air gap of 10 cm.

<u>Sphere-sphere</u>: This section discusses the experiment performed on the sphere-sphere setup. In this setup, two identical spheres of radius 65 mm are placed 100 mm apart. One sphere is subject to an impulse voltage and the other is grounded. The grounded sphere has two grounding points. This is to increase the number of paths to the ground for the impulse to ensure that after the peak the impulse dies quickly [7]. One of the grounding conductors is made up of a thick copper sheet, this to reduce the inductance in the system. The other sphere is connected to the impulse voltage. The up and down method used is outlined in the previous section. The initial voltage Vi in the experiment is determined by a number of iterative tests, these tests include applying a certain voltage to the setup and observing the results if there is a breakdown the voltage is decreased until there is a withstand and breakdown separated by one level of change. Once the initial voltage is determined, the experiments are performed. The output voltage is recorded from the oscilloscope that has a conversion ratio of 157,453. The breakdown is observed on the spheres, if there is a spark then there is a breakdown, otherwise, there is withstand. Additionally, a voltmeter values are recorded, this is to observe the voltage produced by the Marx generator. The results observed in this experiment is recorded in table .1

Table 1: Sphere - sphere results

Voltage level (i)	Output voltage (V)	Number of breakdowns (N_B)	Number of withstands (N_W)
3	1.60	4	0
2	1.56	2	4
1	1.52	5	2
0	1.48	0	4
Total		11	10

The above table shows the results obtained in the laboratory experiment. These values will be used to calculate the 50 % breakdown voltage for the sphere-sphere gap. The equations used are presented in [2]. Figure 2A in appendix A shows the results of the up and down method for the sphere-sphere gap.

$$V_{50} = V_0 + \Delta V \left[\frac{A}{N} \mp \frac{1}{2}\right] \qquad (1)$$

$$N = \sum_{i=0}^{k} n_{iw} \text{ or } N = \sum_{i=0}^{k} n_{ib} \qquad (2)$$

$$A = \sum_{i=0}^{k} i n_{iw} \text{ or } A = \sum_{i=0}^{k} i n_{ib} \qquad (3)$$

Where:

V_{50} = 50 % breakdown voltage (V)

V_0 = Initial voltage (V)

ΔV = Voltage steps (V)

N = The sum of the number breakdowns or withstands

A = The sum of the number of breakdowns or withstands multiplied by the voltage level

n_{iw} = Number of withstands

n_{ib} = Number of breakdowns

The number of breakdowns is greater than the number of withstands (i.e. $N_B > N_W$). Thus the sign in equation 1 is positive and the number of withstands is used for the calculations.

Table 2: Calculated parameters

Parameters	Calculated values
$\boldsymbol{N}$	10.00
$\boldsymbol{A}$	15.20
$\boldsymbol{\Delta V}$	0.040 V
$\boldsymbol{V_{50}}$	1.550 V
$\boldsymbol{V_0}$	1.480 V

The 50 % breakdown voltage is 1.55 V as presented in table 2. This value makes sense when looking at the results presented in table 1. In actual values, this voltage is 244.05 kV. The comparative analysis will include the calculated voltage and this voltage. Furthermore, the correction factor will be applied to this voltage to factor the environmental conditions.

<u>Rod-plane setup:</u> The same procedure used for the sphere-sphere gap is applied in this configuration. In this setup, the plane is grounded and the rod is excited with an impulse voltage. The air gap is 10 cm and the dimensions of the rod and plane are presented in appendix C (prelab).

Table 3: rod-plane physical experiment results

Voltage level (i)	Output voltage (V)	Number of breakdowns (N_B)	Number of withstands (N_W)
3	0.70	2	0
2	0.68	6	2
1	0.66	4	6
0	0.64	0	3
Total		12	11

This case is similar to the sphere gap in that, the number of breakdowns is greater than the number of withstands. Hence, the positive is used in equation 1. The same equations used for sphere gap is used in this setup. The results obtained from the calculations are presented in table 4.

Table 4: Rod-plane configuration results

Parameters	Calculated values
$\boldsymbol{N}$	11.0
$\boldsymbol{A}$	10.0
$\boldsymbol{\Delta V}$	0.02 V
$\boldsymbol{V_0}$	0.64 V
$\boldsymbol{V_{50}}$	0.67 V

The 50 % breakdown voltage for rod-plane is calculated to be 0.67 kV. Using the conversion factor on the oscilloscope the voltage is calculated to be 105.21 kV. This is approximately half the voltage found in a sphere gap for the same air gap. The reason for this difference is presented in the discussion and analysis section.

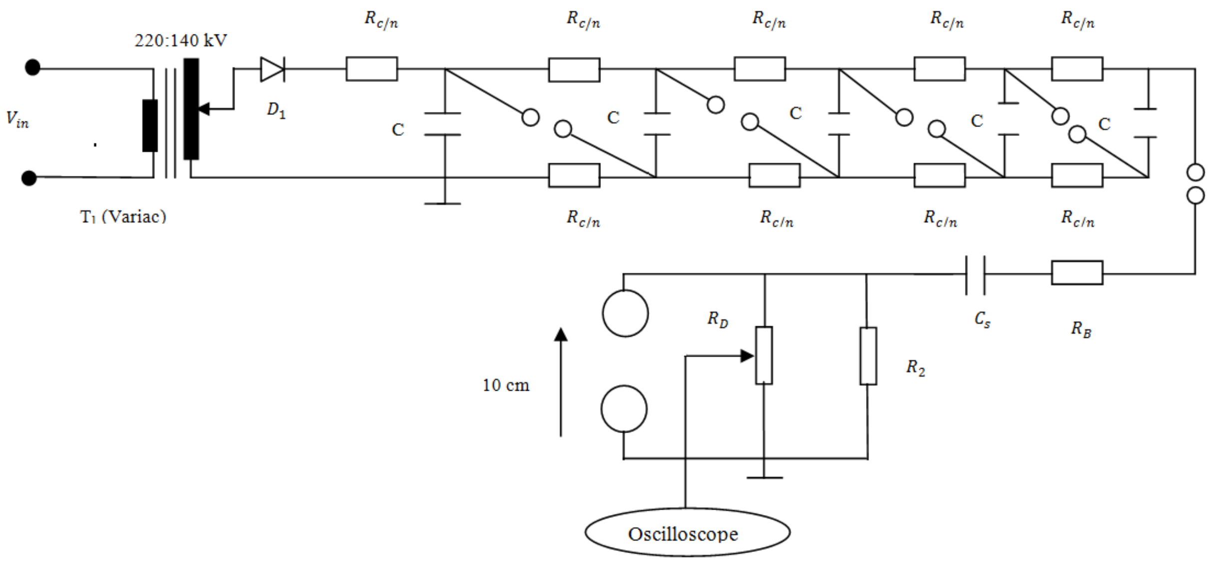

Figure 1: Up and Down experimental setup (five stage Marx generator)

Figure 1 above, shows the setup used in the physical experiment in the laboratory. A variable transformer is connected to the 5 stage Marx generator as shown in the diagram. D_1 is a forward biased diode used to reject current from going back to the source. The rating of the diode is 20 mA, 5 kV. The resistor labeled R_B is the bleeder resistor. This resistor is connected to a capacitor C_2, this connection enables the shaping of the voltage, to produce an impulse. The bleeder resistor R_B is a bandage, this is chosen so that parasitic effects such as unwanted inductance, and capacitance are eliminated [8].

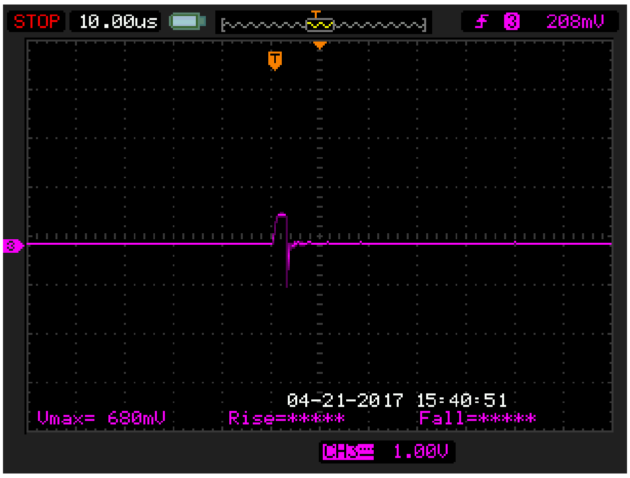

Figure 2: Breakdown voltage for Rod-plane configuration

Figure 2 shows the screen shot obtained from the oscilloscope in the laboratory. This voltage caused the breakdown to occur on the rod-plane configuration. The recorded voltage is 680 mV. Using the oscilloscope conversion factor the voltage corresponds to 104.35 kV.

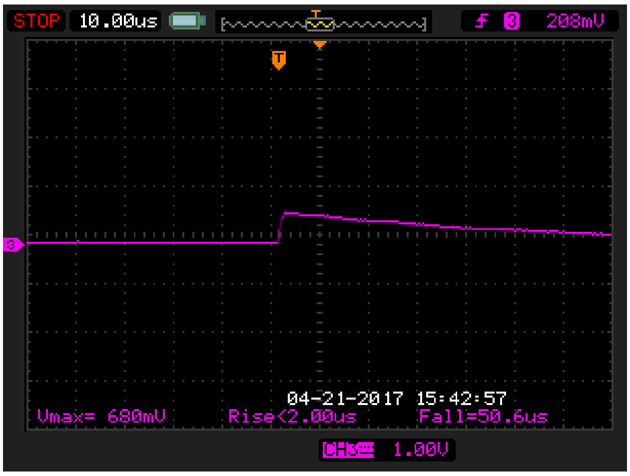

Figure 3: Withstand voltage for Rod-Plane Configuration

Figure 3 shows the withstand voltage for Rod-Plane configuration. This voltage as shown is equivalent to the breakdown voltage shown in figure 2. Table 2 shows that 7 breakdowns occurred for 680 mV and 3 withstands occurred for the same voltage. Hence, the two graphs have the same voltage for different conditions.

Figure 4 shows the breakdown voltage recorded for the sphere-sphere configuration. However, according to the measurements taken, this voltage did not cause any breakdown. This error is a result of the malfunctioning of the oscilloscope. This happened in the laboratory when the voltage is increased or decreased the voltage on the oscilloscope did not change accordingly. Hence, the correct breakdown voltage is 1.56 V, which corresponds to 245.63 kV.

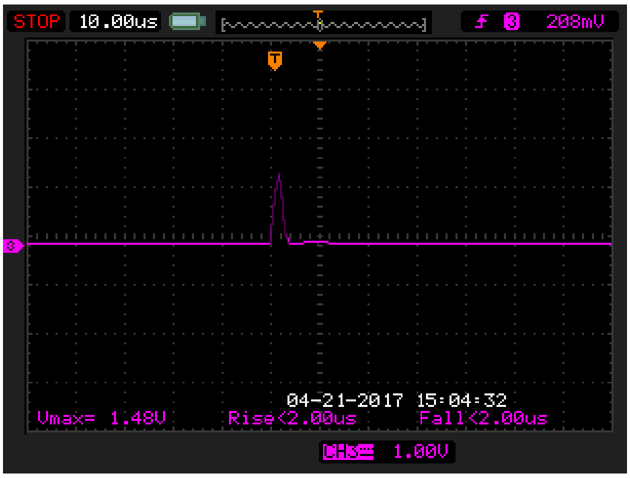

Figure 4: Breakdown voltage for Sphere-sphere configuration

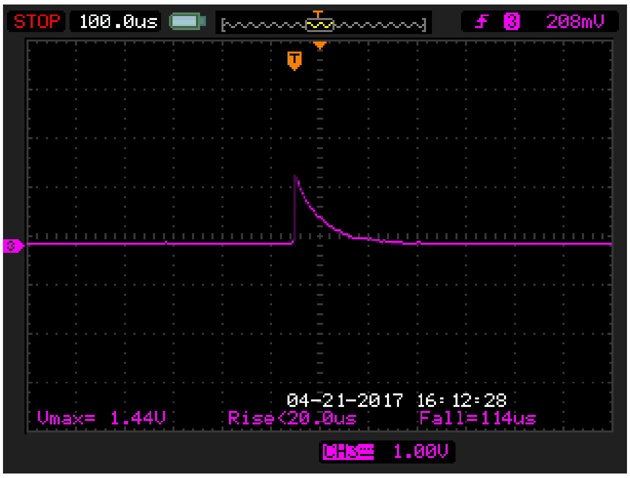

Figure 5: Withstand voltage for sphere-sphere configuration

Figure 5 presents the voltage recorded for the sphere air gap. However, in the laboratory results presented in table 1 the minimum voltage recorded is 1.48 V. This error is due to the same error mentioned for the breakdown voltage in figure 4. The correct withstand voltage is 1.48 V, which corresponds to 233.03 kV.

<u>Correction factor</u>: This section uses the guide presented by the SANS 60060-1 for converting the measured voltages to standard conditions. This section discusses the air density correction factor K_1 and the humidity correction factor K_2 .The disruptive discharge voltage is proportional to the atmospheric correction factor K_t , which is given by equation 4.

$$K_t = K_1 K_2 \qquad (4)$$

By applying the correction factor, the breakdown voltage determined in the laboratory under the environmental conditions presented in table 5 may be converted to standard atmospheric conditions. By applying this conversion the simulated and calculated can be compared with the measured results.

Table 5: Atmospheric conditions recorded in the laboratory

Parameter	Values	Standard atmospheric
Temperature	20.56 ℃	20 ℃
Pressure	0.836 bar	1.013 bar
Humidity	26 %	50 %

The standard procedure outlined in [3] is used. The new 50 % breakdown voltage is calculated using equation 5. Where U50 is the new 50 % breakdown voltage and U is the 50 % measured breakdown voltage.

$$U_{50} = \frac{U}{K_t} \qquad (5)$$

To calculate K_t the correction factor components are required. The air density factor is given by equation 6, where t and P are the measured temperature, and pressure shown in table 5. P_0 and t_0 are the atmospheric pressure and temperature. Equation 6 estimates to equation 7 because m is approximately 1, this is presented in the SANS 60060-1.

$$K_1 = \delta^m \qquad (6)$$

$$K_1 = \delta = \frac{P}{P_0} \times \frac{273 + t_0}{273 + t} \qquad (7)$$

The humidity correction factor is calculated using equation 9. Where k is the parameter that depends on the type of test voltage and can be estimated to 1 similar to m in the air density factor.

$$K_2 = k^w \qquad (8)$$

$$K_2 = k = 1 + 0.010(h/\delta - 11) \qquad (9)$$

$$h = \frac{6.11 \cdot R \cdot e^{\left(\frac{17.6 \cdot t}{243 + t}\right)}}{0.4615 \cdot (273 + t)} \qquad (10)$$

In equation 9, h is the absolute humidity and δ is the relative air density factor. Furthermore, equation 9 applies for an impulse voltage and h/g ratio should be between 1 g/ m^3 and 20 g/ m^3.

The parameters calculated to determine the 50 % breakdown voltage under standard atmospheric temperature are presented in table 6.

Table 6: Calculated 50 % voltages for standard atmospheric conditions

Parameters	Values
K_1	0.823
K_2	0.993
K_t	0.817
U_{50} (Sphere -Sphere gap)	199.45 kV
U_{50} (Rod-Plane gap)	85.957 kV

Results discussion*:* This section presents the discussion between the measured results and the simulated results. The simulated results are presented in appendix C (prelab). Furthermore, answers to laboratory questions are presented in this section. The numerical methods presented in [9 -13] are used to determine the initial breakdown voltage for both sphere-sphere gap and rod-plane gap. The calculated voltage is then applied to FEM to determine the 50 % breakdown voltage. The breakdown voltage is gathered by using the electric fields between the electrodes. The simulation assumes standard conditions, hence the breakdown electric field is 3 kV/mm [14].At this electric field, the voltage is recorded, this voltage is the 50 % breakdown voltage. The table shows the results.

The up and down method is used to calculate the 50 % breakdown voltage, the voltage is then converted to standard atmospheric conditions. The results for both simulations and experiment are presented in table 7. Additionally, the rod-plane voltage is smaller than in sphere-sphere configuration because of the arrangement around the electrodes, in the spheres field spread over the spheres and on the rod is concentrating on one point.

Table 7: Measured and simulated results

	Rod-plane configuration	Sphere-sphere configuration
Simulated	199.45 kV	210 kV
Measured	85.957	90.0 kV
Error	4.49 %	5.02 %

The error in these results is due to several factors such as inaccuracy measurements for the air gap, the fact that the electrodes used are not ideal like in the simulations, the spheres have an uneven surface and might be dirty, and there are parasitic effects of the equipment. The temperature, humidity, and pressure values recorded in the begging of the experiment might not be the same during the entire period of the experiment. Additionally, an error may be due to human error.

<u>Answers to lab questions</u>

What are the alternative ways of obtaining the U_{50} voltage compare these methods with the up and down test?

Alternative ways to obtain U_{50} uses the multi-level-tests and the progressive stress sets. These tests are similar to the up-and-down tests because they all uses statistics to predict the U_{50} voltage [3].

Give three environmental factors that can affect the experiment and state how the U_{50}value may be altered by these values?

Temperature, humidity, and pressure are the environmental factors that can affect the experiment. Pressure and humidity are directly proportional to the breakdown voltage while the temperature is indirectly proportional.

Can a multistage generator be approximated by a single stage generator?

Yes. However, a major restriction is the physical construction where sufficiently large generator becomes expensive and impractical [3].

4. Partial discharge measurement

This section presents the PD tests results and analyses. The tests are split into two sections, the internal discharge, and corona discharge. Internal discharges occur in voids or cavities within a liquid dielectric and corona discharges take place in the gaseous dielectric in the presence of inhomogeneous fields [6]. The internal discharges in this experimented are investigated using polyethylene sheets placed inside transformer oil. The aim is to investigate the effect of air voids in the insulator. To do this, tests of unknown devices are conducted and using the simulation results and relevant literature the position of the voids is identified inside the insulator. The corona discharge test performed using ogura needle. In the tests different concepts are analyzed, these include the inception voltage, extinction voltage, and Trichel pulses.

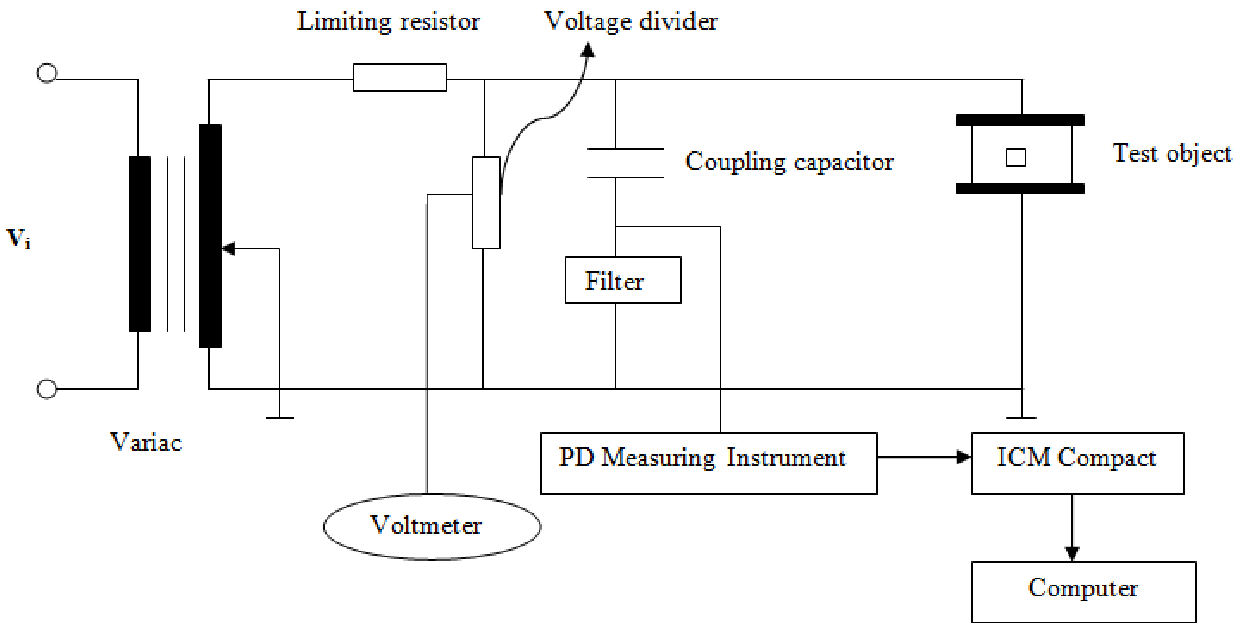

Figure 6: Experiment setup for partial discharge test

The laboratory setup diagram is presented in figure 6. A variable transformer is used as an input voltage to the circuit. The limiting resistor is used to limit the current that is going to the load, which is test object. The test object is the device being investigated, in this experiment it is a polyethylene insulator inside oil subjected to air **voids and the ogura needle.**

Calibration: The calibration process is essential to ensure the accuracy of the measurements. A calibration tool is used on the PD measuring instrument compensate for noise. The noise is due to the energy in the room, this is in a form of electromagnetic emissions (i.e. light and heat) and acoustic emissions (i.e. audible and ultrasonic ranges) [4]. The calibration tool inserted a charge of 10 pF to compensate for the noise.

Inception voltage: This section presents the results obtained for inception voltage measurements. An inception voltage is the lowest voltage where partial discharge process begins [15].

Two unknown devices and ogura needle were investigated. The aim is to predict the position of the void in the insulator if there is any. The literature presented in [16, 17] and the simulations presented in appendix C (*prelab*) are used to analyze the experiment results.

To presented the inception voltage gathered from the ICM compact a number of graphs are presented. The voltage and charge graphs are also presented in this section.

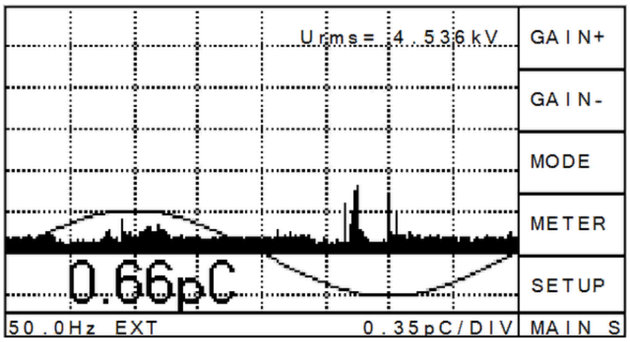

Figure 7: Noise before inception voltage unknown device 1

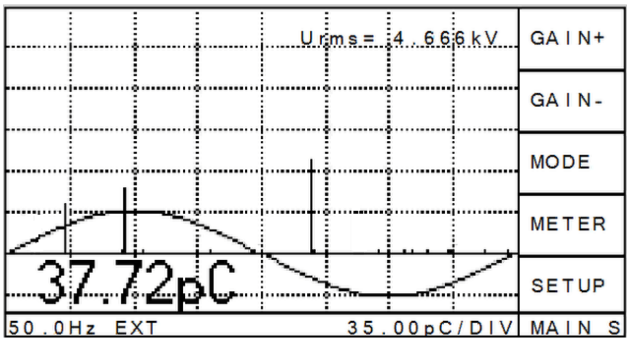

Figure 8: Inception voltage unknown device 1

For the voltages from (0 – 4.536 kV) the ICM compact reading is noise, the first voltage transition from the noise to the partial discharge readings is the inception voltage. Figure 7 shows the inception voltage at 4.666 kV with a charge of 37.72 pC.

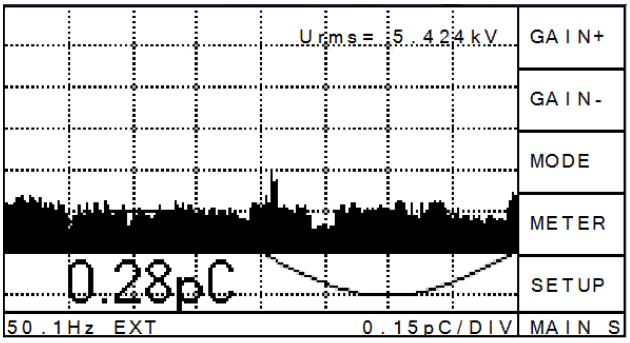

Figure 9: Noise before inception unknown device 2

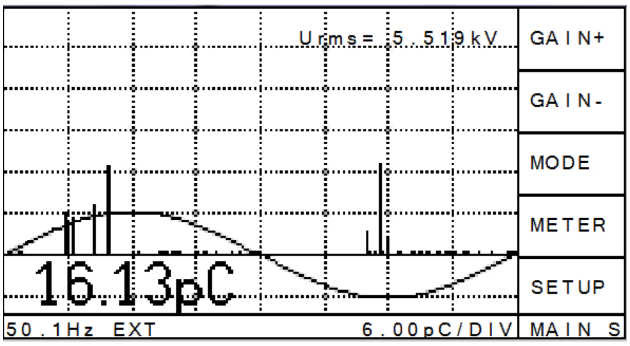

Figure 10: Inception voltage unknown device 2

The inception voltage for unknown device two is shown in figure 10. This voltage is greater than the voltage measured for unknown device one in figure 8.

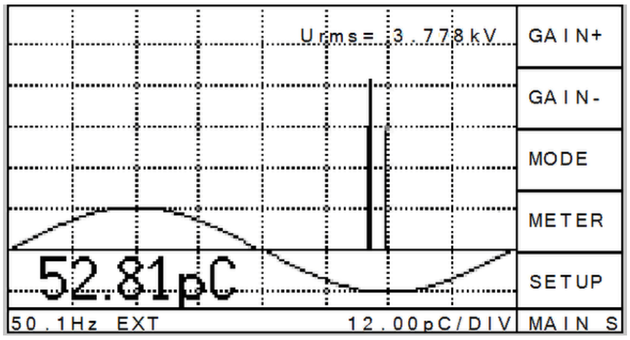

Figure 11: Negative inception for ogura needle

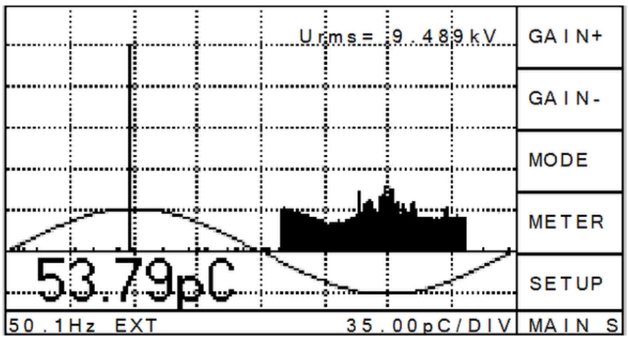

Figure 12: Positive inception for ogura needle

Figure 11 and 12 shows the negative and positive inception respectively. The negative inception is at 3.778 kV while the positive inception is at 9.489 kV.

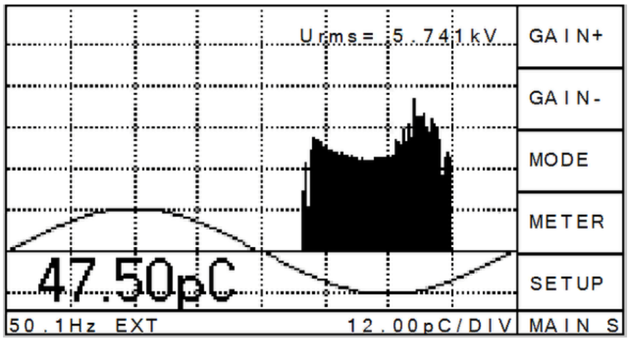

Figure 13: Trichel pulses

Figure 13 shows the Trichel pulses that occur after the negative inception. These pulses can also be seen on the positive inception graph in figure 12.

Extinction voltage: This section presents the extinction voltage for all the devices tested. This is the voltage at where partial discharge stops [18].

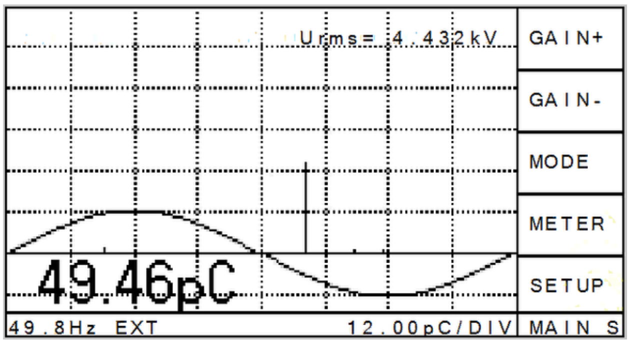

Figure 14: Extinction voltage for unknown device 1

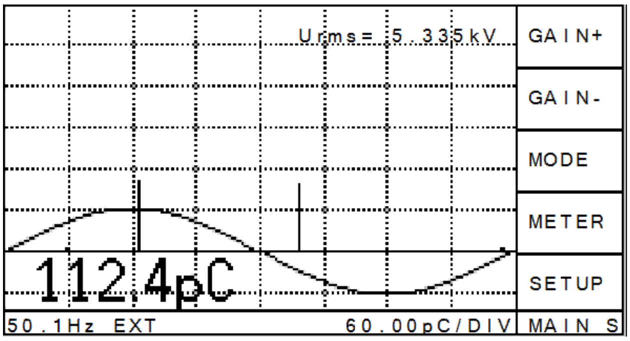

Figure 15: Extinction voltage for unknown device 2

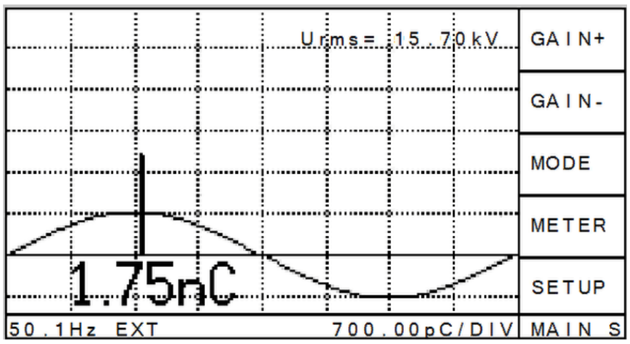

Figure 16: Positive extinction voltage for ogura needle

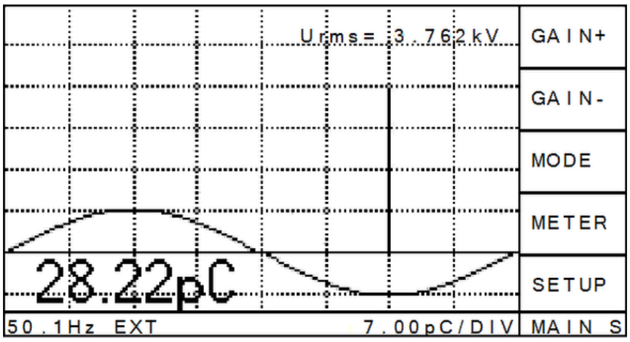

Figure 17: Negative extinction voltage for ogura needle

Analysis of these graphs is presented in the discussion section. Furthermore, more graphs are presented in appendix B.

Partial discharge: This section presents the results of partial discharge measurements. Additionally, the prediction of the unknown devices is presented.

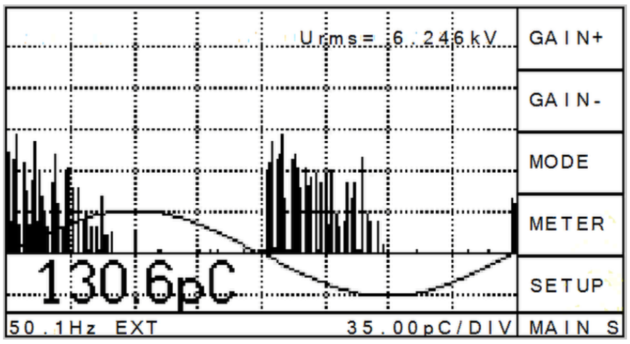

Figure 18: Partial discharge measurements for unknown device 1

To analysis of the graph is based on the method presented in [] for Phase Resolved Partial Discharge Patterns (PRPDP). Furthermore, the inception voltages determined using the FEM simulation are used to predict which device is presented in the unknown device.

To determine the position two important factors must be taken into considerations, that is the distribution of the PRPDP along the positive and negative cycle, the other factor is the magnitude of the inception voltage and the charge. In figure 18, the pattern for the negative and positive cycle is similar in both magnitude and density; this means the void in the insular is approximately in the middle.

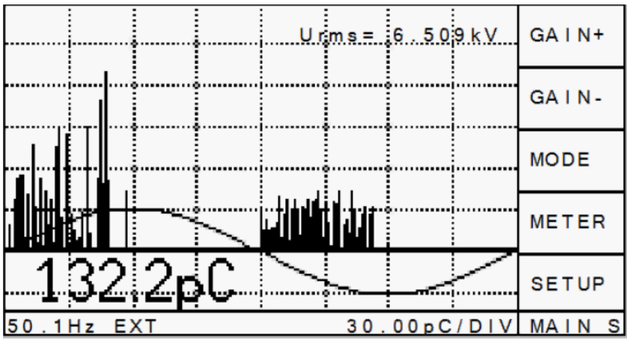

Figure 19: Partial discharge measurements for unknown device 2

Figure 19 shows the partial discharge measurement for unknown device 2. The magnitude of the PRPDP in the positive is slightly higher than the negative cycle PRPDP. Hence, the void is closer to the positive electrode.

Table 8: Measurements summary

	Unknown device 1	Unknown device 2
Inception voltage	4.66 kV	5.519 kV
Extinction voltage	4.432 kV	5.335 kV
Inception charge	32.72 pC	16.13 pC
Extinction charge	49.46 pC	112.4 pC

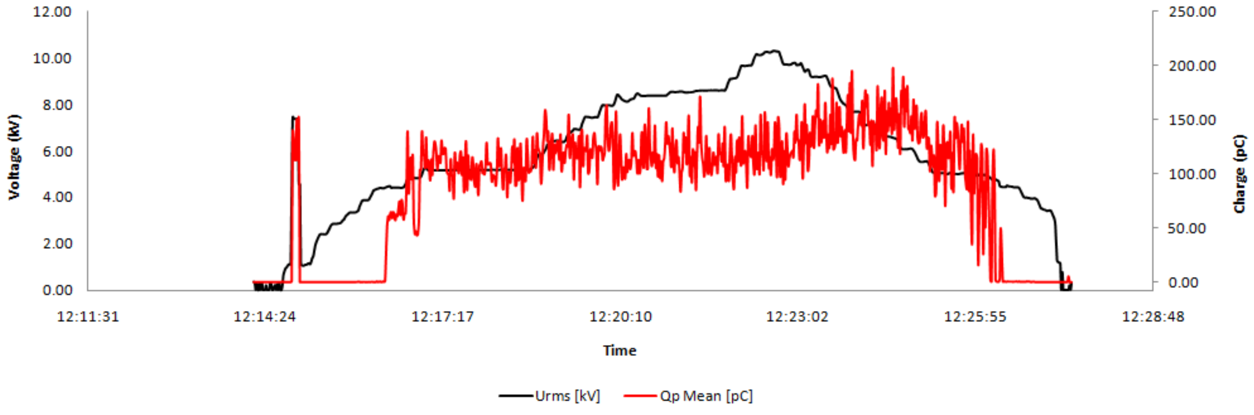

Figure 20: Unknown device 1 Time vs. Voltage and Charge

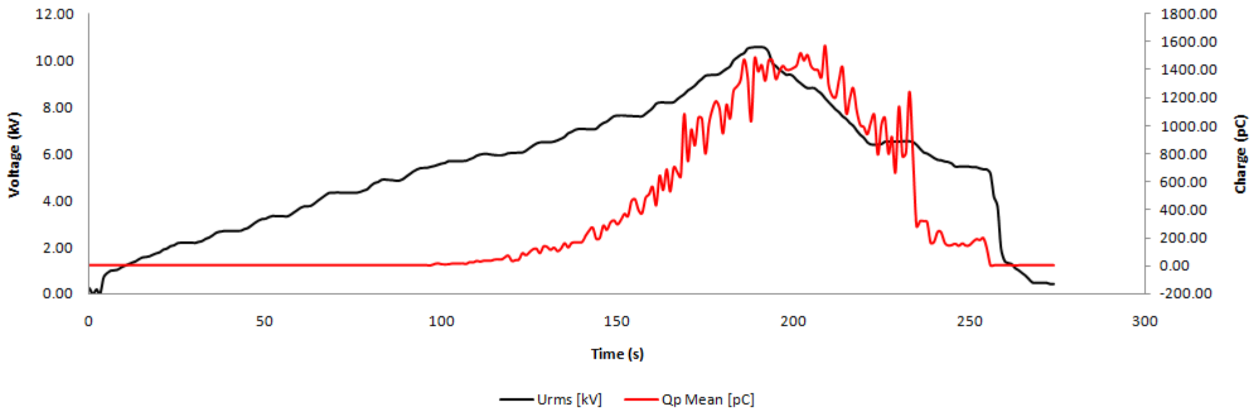

Figure 21: Unknown device 2 Time vs. Voltage and Charge

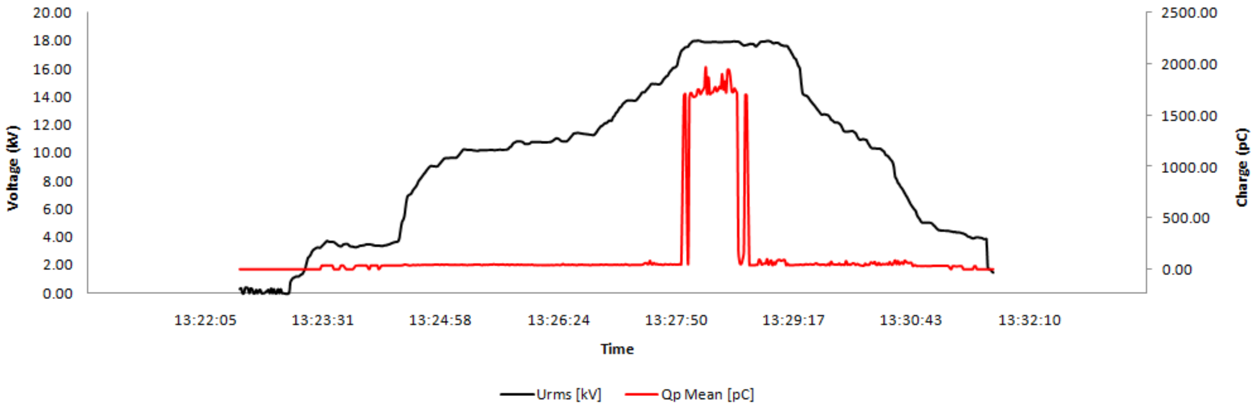

Figure 22: Ogura needle Time vs. Voltage and Charge

5. Results discussion and analysis

This section discusses the results presented in the previous section. The discussion is in a form of questions and answers.

Why is calibration necessary?

Calibration is a process used to make measuring equipment accurate by compensating for the error, which may be present in the facility [19].

Why is the inception voltage different from the extinction voltage?

The inception voltage is not the same as the extinction voltage because when the voltage is decreased there are residual charges in the cavity [20].

Why is the inception and extinction voltage of unknown device 2 greater than that of unknown device 1?

The void in unknown device 2 is bigger than in unknown device 1, hence more voltage is required to cause partial discharges in unknown device 2.

What is corona and how does it affect electrical equipment?

Corona is self-sustained electrical discharges where the field intensified ionization is contained over a portion of the distance between the electrodes [21]. Coran can reduce the reliability of electrical systems by degrading the insulation [22].

What do the Trichel pulses in the figure represent?

This is basically pulsating current mode in the negative corona discharge [23] and they only occur in electronegative gasses.

Why do the negative inception and extinction voltage come before the positive inception and extinction voltage in the ogura needle experiment?

This is because the air is an electronegative gas, thus it a high tendency of absorbing free electrons to form an anion [23]. Hence air has more electrons which are negative.

Why does corona make a hissing noise and why is it orange?

When the potential difference is increased beyond the threshold of air, the fields strength increases and the surrounding experiences stress which causes the air to be conducting results in the noise, orange color and odor [24]. The collision of electrons due to this process produces an orange color.

6. Conclusion

This document presents two experiments conducted at the high voltage laboratory. The experiments are used to examine the behavior of insulators under high voltage. The first test includes testing the strength of air under high voltage. The sphere-sphere and rod-plane configurations are used to perform to determine the 50 % breakdown voltage. The up and down method is used to determine the 50 % breakdown voltage. The U_{50} is 199.45 kV and 85.975 kV for sphere-sphere and rod-plane configuration respectively. Furthermore, the error between the simulated and measured results is approximately 5 %.

The second test is a partial discharge experiment. In the experiment, the effects of voids in insulators are examined. Two unknown devices are tested. The aim of this is to estimate the location of the void in the insulator. In the first device, the void is found to be in the middle and for the second device, the void is found to be near the positive electrode at the top. Finally, the ogura needle is tested to test for corona.

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Appendix A

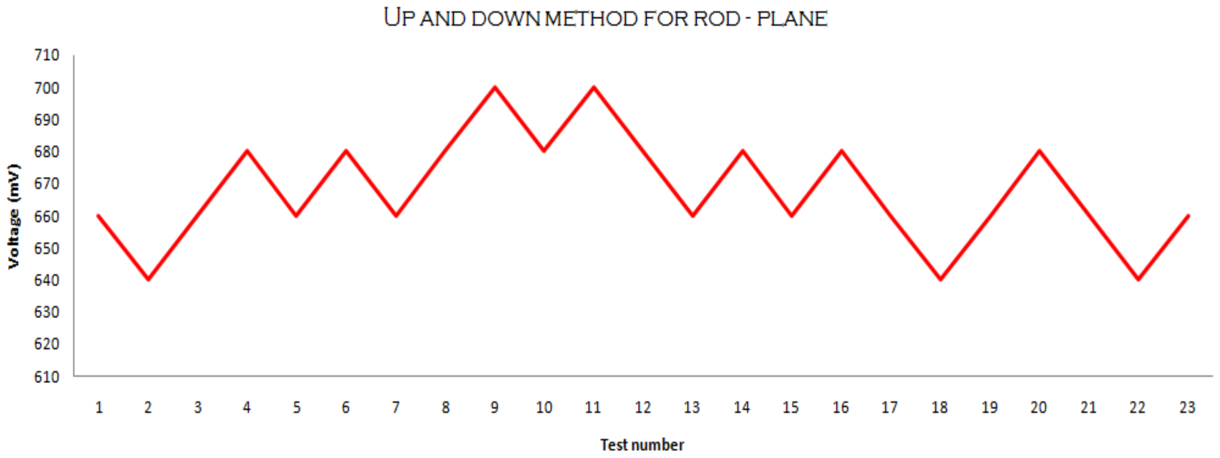

Figure 1A: Rod-Plane Up and down method

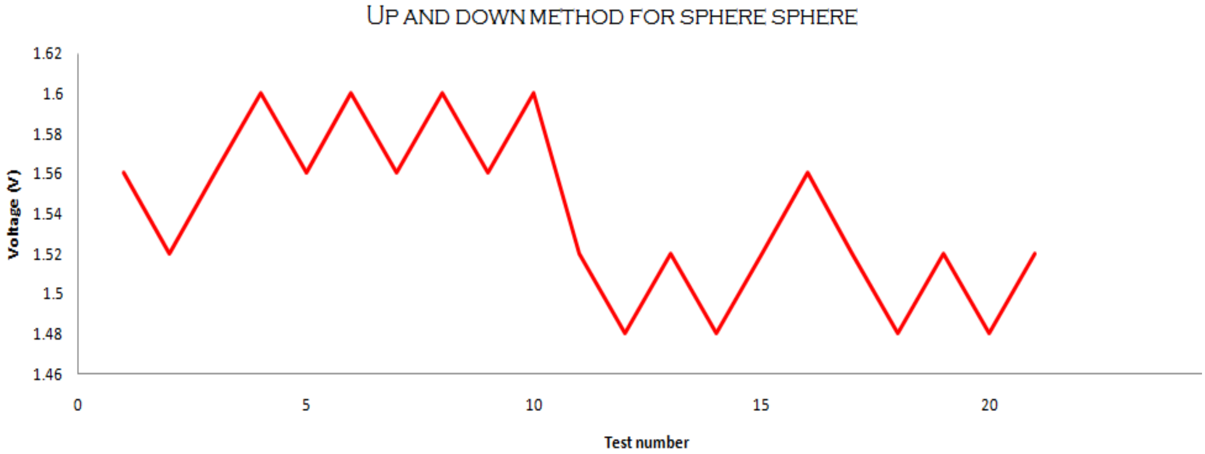

Figure 23: Sphere-Sphere and down method