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ANALYSIS OF DC BREAKDOWN CHARACTERISTICS IN DIFFERENT TYPES ELECTRODES

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Abstract

The use of High Voltage (HV) apparatus in the HV transmission line has been in high demand since the realization of two main electrical power transmission approaches, High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC). In accordance with the vast growth of HV apparatus design industry, innovative HV apparatus designs have become one of the most crucial subjects to address specific high-power transmission issues for better efficiency. For education purposes, HV laboratories in universities use electrodes that come in different shapes and sizes with other HV apparatus to study the breakdown characteristics of dielectric materials due to differences in the input voltage. For this research, the DC breakdown experiment using different electrode shapes and different air gap distances was first conducted in an actual HV laboratory to obtain breakdown voltages data and then simulated numerically through COMSOL Multiphysics. In the software, the Finite Element Method (FEM) was used to simulate the electric field strength for different types of electrodes namely sharp point electrode, cylindrical electrode, and the spherical electrode to study the behaviour of electric field strength around the respective electrodes.

Keywords: Breakdown characteristic, DC breakdown, Electric field strength.

1. Introduction

Electrical breakdown, also known as the dielectric breakdown is a phenomenon that when current flows through a dielectric material, and experience sufficient stress, the voltage across it exceeds the breakdown voltage and the material becomes conductive. Breakdown voltage is the minimum voltage required to make a dielectric material conductive.

It is known that the highest accepted absolute humidity value for any DC breakdown is merely 13 g/m^3. The absolute humidity value of Malaysia is similar to that of Thailand that is mostly above 13 g/m^3. Chotigo and Boonwern [1] used sharp rod electrodes with various tip angles with the dielectric as air, found that the DC breakdown voltage increases as the absolute humidity greater value increases and the absolute humidity value does not have significant effect on DC breakdown when it comes to small line-to-ground gap but will have larger effect at larger distances.

Moreover, the study of high voltage also explains how ambient temperature, the material of the electrode, the gap distance between two electrodes are going to affect the breakdown voltage level of an electrode massively. DC breakdown experiment is conducted in three different air density, (K_b) and atmospheric factor, (K_t) of 13.5 g/m^3, 18.25 g/m^3, and 20 g/m^3. (*atmospheric factor is a product of air density factor and humidity factor). Tables 1 to 3 show detailed results.

Table 1. Breakdown voltage test for 30° electrode tip and 20 g/m^3 [1].

Rod-rod gap 30° at 20 g/m^3		
Gap distance (cm)	**K_b (kV)**	**K_t (kV)**
2	23.5	26.6
4	46	52.1
8	56.8	64.3
12	71.5	80.9

Table 1. Breakdown voltage test for 45° electrode tip at 20 g/m^3 [1].

Rod-gap 45° at 20 g/m^3		
Gap distance (cm)	**K_b (kV)**	**K_t (kV)**
2	28.4	32.1
4	47	53.2
8	60.7	68.7
12	75.4	85.3

Table 2. Breakdown voltage test for 60° electrode tip at 20 g/m^3 [1].

Rod-rod gap 60° at 20 g/m^3		
Gap distance (cm)	**K_b (kV)**	**K_t (kV)**
2	40	45.4
4	49	55.4
8	63.7	72
12	82.3	93.1

In these tables, they had shown that the breakdown voltage for K_b and K_t is increasing exponentially as the rod-to-rod gap distance increases. When the humidity factor is taken into consideration, the breakdown voltage for K_t has increased drastically compared to K_b. For 2 cm rod-to-rod gap distance, the breakdown voltage level raises from 23.5 kV to 26.6 kV for 30° tip angle, 28.4 kV to 32.1 kV for 45° tip angle and 40 kV to 45.4 kV for 60° tip angle. For 12 cm rod-to-rod gap distance, the breakdown voltage increased from 71.5 kV to 80.9 kV for 30° tip angle, 75.4 kV to 85.3 kV for 45° tip angle and 82.3 kV to 93.1 kV for 60° tip angle.

Hussian et al. [2] explained that another research has also shown how the electrode distance gap, humidity, and ambient temperature affects the breakdown characteristic of both sphere-to-sphere and a rod-to-rod electrode that is being placed by using the up and down method. The changing parameters are as follow.

Sphere-to-sphere

- Detects breakdown based on humidity variation of 11 g/m^3 to 16 g/m^3 at an ambient temperature of 20° celsius and 13 g/m^3 to 25 g/m^3 at an ambient temperature of 27° celsius.
- The sphere-to-sphere electrode distance gaps are 5 cm, 7.5 cm, 10 cm and 12.5 cm. (One sphere has a 25cm diameter)

Rod-to-rod

- Humidity variation starts from 11 g/m^3 to 16 g/m^3 at an ambient temperature of 20° and 27° Celsius.
- Gap spacing between the rods experiments at 25 cm, 40 cm, 50 cm, 60 cm and 70 cm.

From the result shown above, there are two types of result for which, Fig. 1 is showing the breakdown characteristics of a spherical electrode while increasing humidity from 11 g/m^3 to 16 g/m^3, while Fig. 2 is showing the breakdown characteristics of a rod electrode when humidity is increasing from 11 g/m^3 to 16 g/m^3.

The overall result for this paper has shown in Fig. 1, that the spherical electrode consists of a unique characteristic, which the change in breakdown voltage is insignificant when humidity changes. On the contrary, the breakdown voltage level of a rod electrode is heavily affected by the humidity change. The breakdown voltage at a distance gap for 60 cm is increasing from 173 kV to 225 kV, the same condition is happening drastically towards 70 cm distance gap as it has approximately 187 kV to 260 kV, which validates the statement that breakdown voltage can be heavily affected by the unknowns in the surrounding.

Corona discharge is one type of partial discharge that occurs due to the ionization of the air between the high voltage electrode and low voltage electrode (ground in this paper) [2]. According to Altamimi et al. [3], in IEEE International Conference Power and Energy (PECON), it was found that in Malaysia, the corona inception voltage is the lowest, whereas, the maximum charge magnitude is the highest for the sharp electrode, followed by flat and sphere electrodes. In high voltage engineering, experiments about DC breakdown characteristics for different shapes of electrodes such as rod-to-rod, sphere-to-sphere, flat circle plate-to-plate, and different combination of each other such as rod-to-plate, sphere-to-plate and more are conducted.

Sankar [4] also uses a standard up and down sphere gap electrode experimental setup. The author performed a slightly different approach compared to the previous two papers discussed above, which shows a sphere gap versus breakdown voltage chart and sphere gap versus electric field strength. The experiment will demonstrate how the curves are affected according to Eq. (1):

$$D = \varepsilon E \quad (1)$$

where D symbolizes the electric displacement, ε is the dielectric permittivity of the material and E is the electric field density.

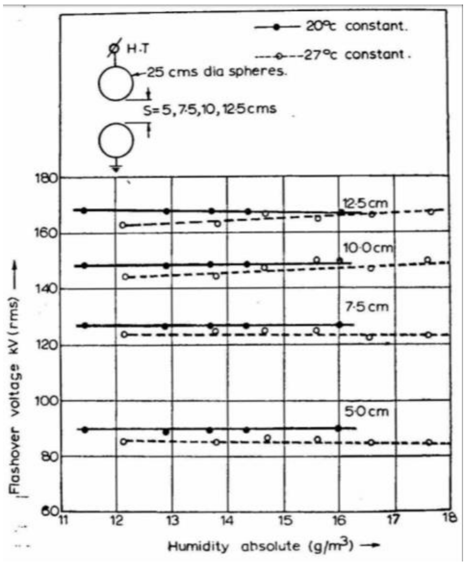

Fig. 1. Effect of varying humidity on breakdown voltage of sphere gap [2].

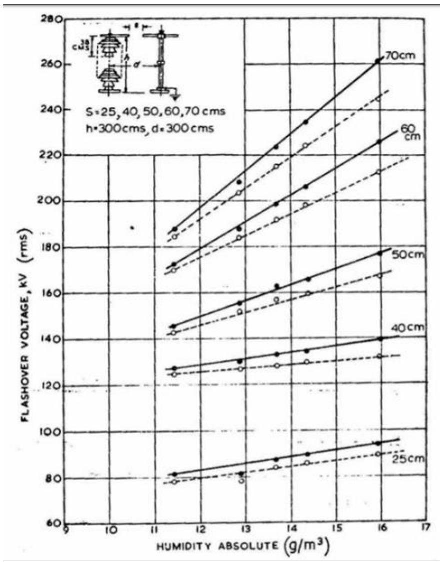

Fig. 2. Effect of varying humidity on breakdown voltage of rod gap [2].

According to Fig. 3, the trend of how the breakdown voltage increases as the gap increases are similar to the research shown above. From Eq. (1), the electric field is directly proportional to the distance of the gap. Figure 4 has proven the equation by choosing 10 different sphere gap points to form a declining trend of the graph.

In Fig. 5, the author uses COMSOL software to simulate the sphere electrode with a 1 cm gap in between both spheres by using finite element method (FEM) to obtain the optimum electric field as shown in Fig. 6. Red represents the strongest electric field strength. As you can see, as the closest point between the two spheres is starting to spread out, the electric field is starting to weaken.

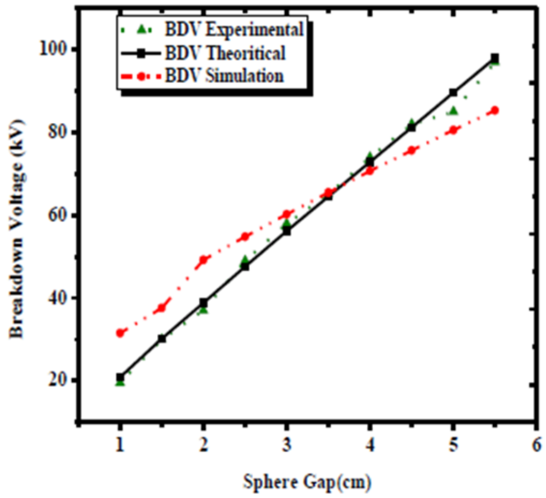

Fig. 3. Breakdown voltage (kV) versus sphere gap (cm) [4].

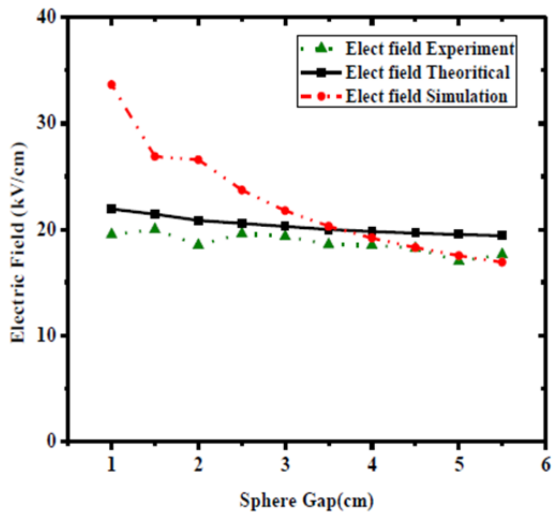

Fig. 4. Electric field (kV/cm) versus sphere gap (cm) [4].

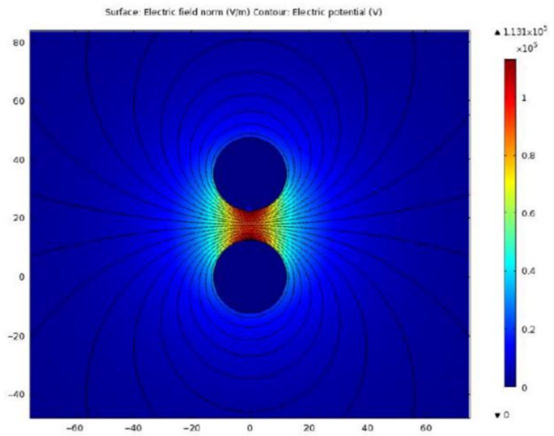

Fig. 5. Electric field between sphere electrodes using FEM in COMSOL software [4].

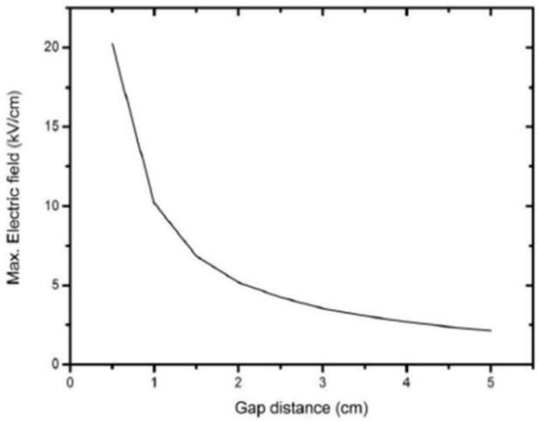

Fig. 6. Simulated value of electric field vs. 1 cm gap distance between two spherical electrodes.

2. Methodology

In the experimental laboratory works, experiments were conducted in an HV laboratory to observe the physical effects of different air gap distances (3 mm, 5 mm, 7 mm, 9 mm, 11 mm) with different electrode shapes (sphere, cylindrical and sharp) of the same material (stainless steel) on the DC breakdown characteristics. For every combination (different air gap distances and different electrodes shapes), HVDC input voltage source was increased slowly until the breakdown of air, seen and heard as a spark on the ground plane occurs. However, from the occurrence of DC breakdown of air, the electric field on each electrode cannot be analysed. The specific location on the electrode where the breakdown occurs cannot be analysed as well. Thus, each DC breakdown voltages for each combination was recorded and tabulated in COMSOL Multiphysics software to perform FEM simulation on electric field strength for each combination to study the effects of electric field strength on DC breakdown of air and to study the location of the breakdown on the electrodes based on the electric field intensity data.

The following Fig. 7 shows the equivalent circuit for the DC voltage generation. Meanwhile, Fig. 8 shows the research workflow from literature review, laboratory experiments and numerical analysis of the DC breakdown characteristics at different air gap distances with different types of electrode used.

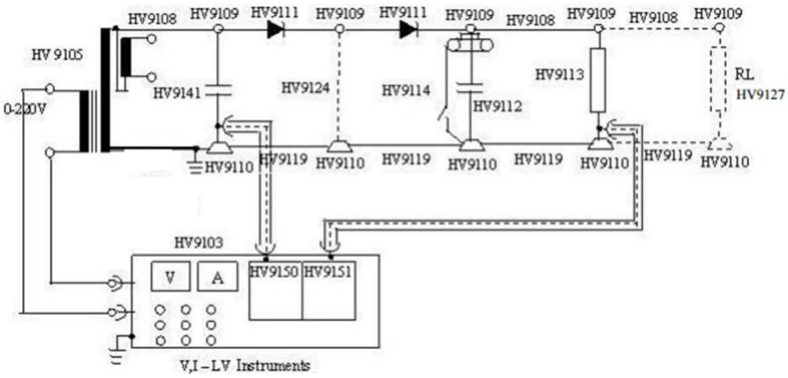

Fig. 7. Equivalent circuit of DC voltage generation.

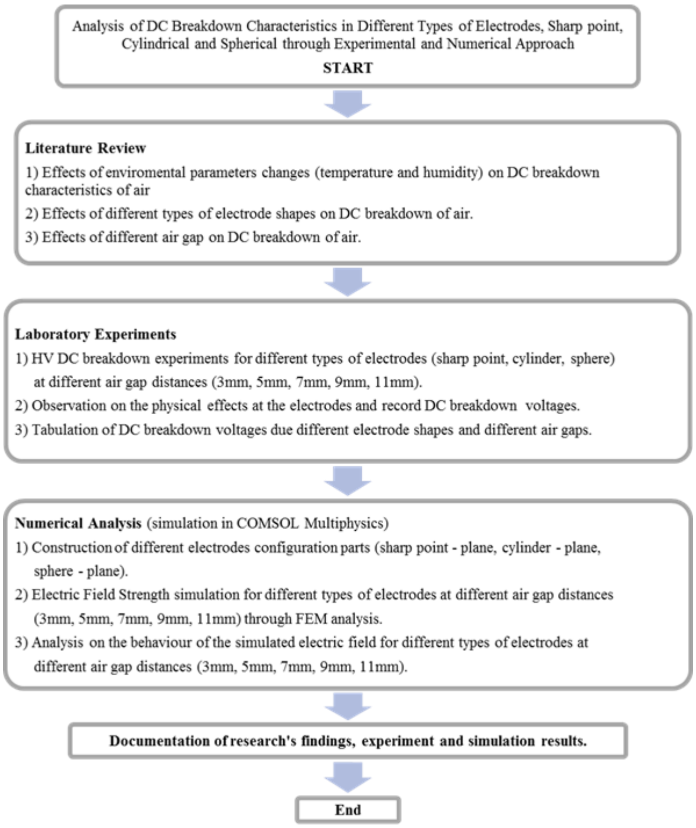

Fig. 8. Research workflow.

3. Experimental Results Analysis

Referring to the equivalent circuit of DC voltage generation presented in the previous section, the equivalent circuit consists of a high voltage transformer, rectification, and DC measurement. The function of the transformer in the circuit was to step up the voltage to higher voltage up to a few tens of kilovolts for this experiment. The rectifier in the circuit was used to convert the high alternating voltage into high direct voltage. Moreover, the capacitor was used to smoothen the rectified DC voltage to prevent ripples.

The resistor was used to resist the current in the circuit. The focus of this research is to analyse the variation of DC breakdown voltage and electric field intensity due to different electrode shapes and different air gap distances. The analysis in this research provides insight into characteristics related to DC breakdown of air and the location on the electrodes of occurrence based on electric field strength. The recorded breakdown voltages from the actual experiment in the HV lab where the absolute humidity is above 13 g/m^3 in room temperature are shown in Table 4 and plotted in Fig. 9.

By comparing the breakdown voltages of the sharp point-plane electrode, sphere-plane electrode and cylindrical-plane electrode, the measured breakdown voltage of sphere-plane electrode is the highest regardless of air gap distance while the measured breakdown voltage for the sharp point-plane electrode is the opposite. By comparing the breakdown voltage of different air gap distances, the breakdown voltage is lowest when the air gap distance is shortest.

Table 5 shows the AC breakdown voltages. According to Tables 4 and 5, the DC breakdown voltages for all the three types of electrode shapes, are higher than AC breakdown voltages. This condition occurs when the AC breakdown voltage is governed by multiple high-intensity discharges. This outcome supports the theoretical finding of the DC dielectric strength of air is higher than the AC dielectric strength.

Table 4. Calculated breakdown voltage and measured dc breakdown voltage.

Air gap distance (mm)	DC measured breakdown voltage (kV)		
	Sharp point-plane electrode	Sphere-plane electrode	Cylindrical-plane electrode
3	8.54	11.90	10.29
5	10.75	18.34	13.85
7	12.47	24.93	16.60
9	13.87	30.00	18.45
11	14.47	34.90	20.04

Table 5. Calculated breakdown voltage and measured ac breakdown voltage.

Air gap distance (mm)	AC measured breakdown voltage (kV)		
	Sharp point-plane Electrode	Sphere-plane electrode	Cylindrical-plane electrode
3	5.20	7.20	6.29
5	6.32	11.60	7.99
7	6.50	13.83	10.20
9	7.87	16.94	11.30
11	8.60	19.22	12.80

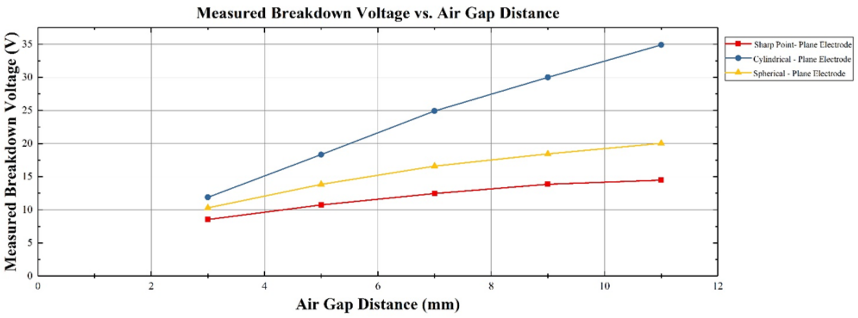

Fig. 9. Graph of measured breakdown voltage vs. air gap distance.

4. Numerical Analysis

Jahangiri et al. [5] and Zhang et al. [6] reported that the computation analysis has been developed in numerous of research, which investigated the effect of field characteristic on electrical devices and equipment. In general, the electric field intensity is much higher in the surroundings of the electrode particularly at the top edges of the sharp point electrode as shown in Fig. 10.

As the plane electrode is a ground electrode, it can be observed that the electric field intensity is very low on the surface of the plate electrode. Although the distance between the top edge of the sharp point electrode and the plane electrode is only a few millimetres apart, the electric field intensity at the top edge of the sharp point electrode is very high but the electric field intensity of the sharp point electrode is very low. In addition, it can be observed that the further the distance from the sharp point electrode, the lower the electric field intensity as shown in Fig. 11. It was found that the maximum electric field intensity is when the air gap distance is 3 mm.

Furthermore, the graph with an air gap distance of 3 mm has the highest initial value (electric field intensity) among the five figures, which is about 37×10^5 V because the air gap distance between the sharp point electrode and the plate electrode is the shortest. On the other hand, the graph with an air gap distance of 11 mm has the lowest initial electric field intensity value among the five figures, which is about 17×10^5 V because the air gap distance between the sharp point electrode and the plate electrode is the furthest.

Figure 12 shows the electric field intensities at different air gap distances from the spherical electrode. By comparing the result of Figs. 11 and 12, the electric field intensity is more uniform and nearer to each other. This shows that the spherical electrode has more uniform electric field intensity compared to the sharp point electrode that has high electric field intensity at the top edges. This is because high electric field intensity occurs at the smaller surface area. The shape of the spherical electrode has a uniform surface area and thus, there is no smaller surface area, and this leads to a uniform electric field intensity. In addition, similar to the findings from the simulation of sharp point electrode, the electric field intensity is inversely proportional to the distance that means the electric field intensity is weaker as the distance increases from the electrode.

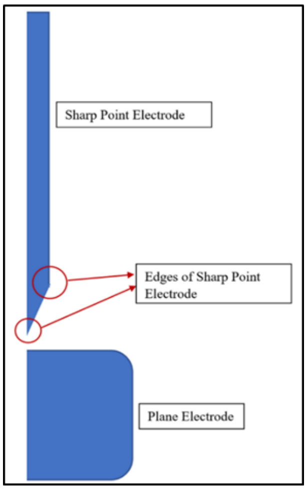

Fig. 10. Sharp point electrodes and plane electrode with labels of edge with maximum electric field.

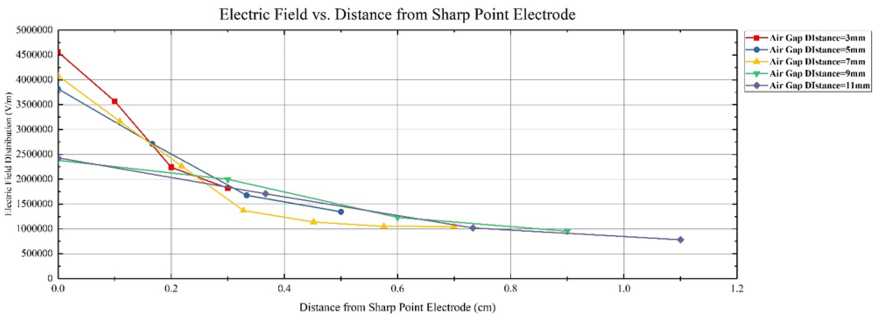

Fig. 11. Graphs of electric field intensity vs. distance from sharp point electrode.

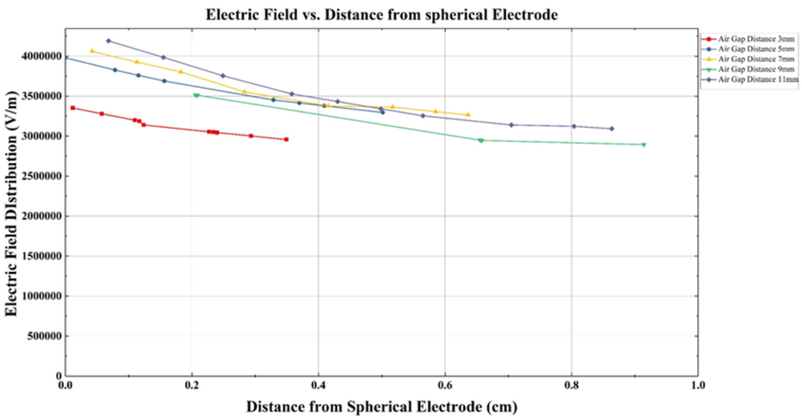

Fig. 12. Graphs of electric field intensity vs. distance from spherical electrode.

5. Conclusions

In conclusion, the characteristic of electrical breakdown under DC voltage with different air gap distances and different shape of electrodes was analysed based on the results obtained from COMSOL simulation. As observed from the simulation results, the sharp point-plane electrode has the highest field intensity compared to the cylindrical-plane electrode and the spherical-plane electrode. This is because the sharp point-plane electrode has a very edge at the top of the surface of the electrode and this makes a very small surface area on the electrode. Thus, high electric field intensity occurs at the top edge of the sharp point electrode. On the other hand, the spherical-plane electrode has the lowest electric field intensity compared to another shape of the electrode. This is because the spherical electrode has s very smooth surface and there is no edge on its surface. From the result, it can be concluded that the breakdown voltage is inversely proportional to the air gap distance. The objective of this experiment has been carried out successfully because the measured breakdown voltage is co-related to the electric field intensity in the simulation results.

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