Evolution in Electrical and Electronic Engineering Vol. 3 No. 2 (2022) 743-753

EEEE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/eeee
e-ISSN : 2756-8458

Experimental Investigation on the DC Breakdown Strength of Air Under Various Field Uniformities

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DOI: https://doi.org/10.30880/eeee.2022.03.02.088
Received 03 July 2022; Accepted 14 September 2022; Available online 30 October 2022

Abstract: The design and durability of the insulation are important in preventing leakage when electrical stress occurs. Therefore, experimental studies were performed on the electrodes by using the surrounding air as insulation. The breakdown strength of five pairs of electrodes, which are the sphere-sphere electrode, rod-rod electrode, sphere-rod electrode, spherical-plane electrode and the plane-rod electrode was tested at distances of 0.5 cm, 1.0 cm, 1.5 cm, 2.0 cm, 2.5 cm and 3.0 cm. This experiment is divided into two parts, which are positive DC breakdown voltage and negative DC breakdown voltage. Then, simulations were performed using Finite Element Method Magnetics 4.0 (FEMM 4.0) software to obtain the electric field intensity for each electrode pair at different distances and the maximum electric field, E_{max}. Several calculations were performed to obtain the parameters required in this study. The relationship between E_{max} and electrode pair distance and breakdown voltage can be studied using the data obtained from the calculation results. The relationship between the field utilization factor and the distance between each electrode pair has also been discussed in this research. At the end of the study, it was found that the sphere-sphere electrode pair produced the highest breakdown voltage which are 73.52 kV and 69.24kV during a positive and negative breakdown, respectively. It also has the lowest E_{max} value which is 27.488 kV/cm, and the highest field utilization factor (0.98) compared to the other electrode pairs. This indicates that the sphere-sphere electrode pair is the best electrode pair due to its shape having a uniform surface.

Keywords: DC Breakdown Strength, Electric Field Intensity, Field Utilization Factor

1. Introduction

An insulator for HVDC application is required to endure specific electrical stress compared to the insulator used in AC application. It is because of the unidirectional flow of electric current and highly non-uniform electric field distribution along the insulator string. The electrical and thermos stress may occur if the stress is not tackled properly in DC insulator design. The factors that affect the performance

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are ionic current, non-uniform voltage distribution due to non-uniform electric field and electrostatic attraction of dust and other particles.

Most of the HVDC system is a place in the sea region and the cable is buried underground. The earth has different layers with varying resistivity. The surface layers of land over the rocks contain many local irregularities of varying resistivity, such as rivers, marshes, and deserts. The location of an electrode must be carefully selected so that there is a plentiful supply of groundwater and the earth's resistivity is low. The electrode is buried at a depth of 1.2 m to 8 m in the ground. The anode is the electrode where the HVDC system's direct current enters. The current returns to the HVDC system via the cathode, which is the electrode on the other end [1]. This is why any overvoltage has to be avoided because if the electrode receives overvoltage, the breakdown might occur and the spark will produce.

1.1 DC Voltage Breakdown

Steady overvoltage on the DC transmission system now is still very rare to be found. It is important to do the overvoltage tests in the laboratory so that the toughness of the designed equipment for steady high voltage can be determined. A high electric field is produced at the tips of electrodes when high voltage is applied to the electrodes. As a result, at any gap, the voltage at which inception occurs at the electrode is lower for a given gap than it is for a uniform field gap. As the voltage is increased to the inception level, the air gap is severely stressed, and corona is initiated from the electrodes. Initiating a streamer is initiated by increasing the voltage. At this point, the streamer may cause a disruptive discharge. When the applied voltage is increased, the streamer is extinguished and a glow forms, which strengthens the gap. The final air breakdown is almost 100 percent greater than the initial streamer that caused the earlier disruptive discharge [2].

1.2 Air As An Electrical Insulator

Air is a mixture of several gasses such as nitrogen (78%), oxygen (21%) and other gasses. This mixture of gasses consists of many molecules that move freely and the most important part is those air molecule is uncharged. That means very high energy is needed to remove the electron(s). It required around 15 electric volts to remove an electron from nitrogen or oxygen [3]. Air is most of the common insulators in the electricity field as it is a very good thermal insulator. The configuration of the air molecule allows the air act as insulator because it has low conductance which is around 3×10^{-15} S/m [4]. Normally, air molecules are assumed to be in a sphere shape. The mean distance between molecules is much greater than the diameter of the molecule. The attraction between molecules depends on the diameter of every atom. Every molecule is moving and hit each other due to the force between the molecules and the wall. To use the kinetic theory of gases invented by Maxwell, the mentioned force must be negligible [5].

1.3 Non-uniform Field

There are few uniform fields in the real world of high voltage engineering. In studies of air breakdown, geometrical non-uniform fields such as point-plane, point-to-point, or coaxial electrodes are commonly used. The results of such tests have resulted in empirical formulae. At the design stage, these formulae are used to estimate the likely breakdown of electrical equipment. The tests have also revealed more details about the processes involved in air breakdown. In non-uniform fields, the electric field is stronger at the electrode than at the rest of the gap. The value of the field has a logarithmic less than its maximum [2].

2. Methodology

In this paper, an experiment was conducted using TERCO procedures and equipment as in [6]. The breakdown strength of five pairs of electrodes, which are sphere-sphere electrode, rod-rod electrode, sphere-rod electrode, spherical-plane electrode and plane-rod electrode were tested at distances of 0.5 cm, 1.0 cm, 1.5 cm, 2.0 cm, 2.5 cm and 3.0 cm. This experiment is divided into two parts, which are positive DC breakdown voltage and negative DC breakdown voltage. The flowchart of experiment is shown in Figure 1. Then, simulations were performed using Finite Element Method Magnetics 4.0 (FEMM 4.0) software to obtain the electric field intensity for each electrode pair at different distances and the maximum electric field, E_{max}. The flowchart of the simulation is shown in Figure 2. Several calculations were performed to obtain the parameters required in this study.

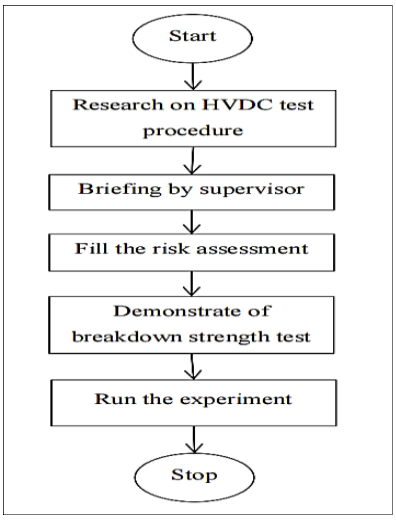


Figure 1: Flowchart of the experiment conducting DC strength breakdown test

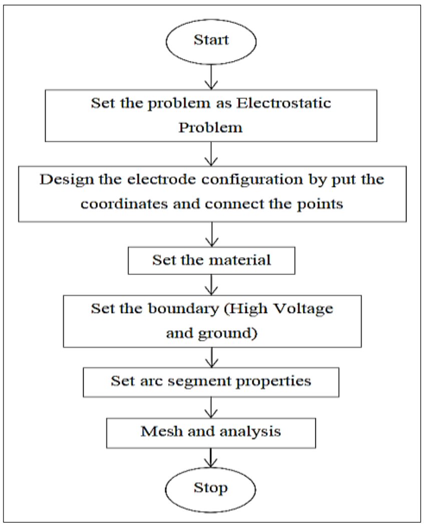
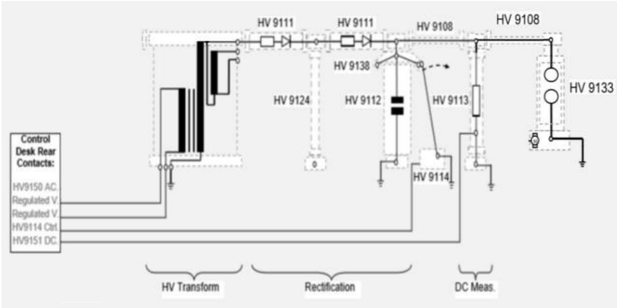


Figure 2: Flowchart of FEMM 4.0 software simulation

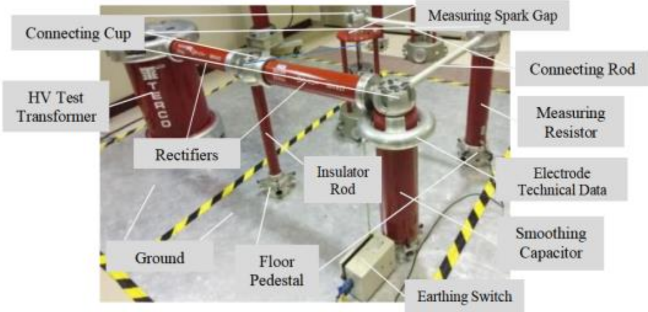
2.1 Experiment Set-up

The test has been performed at room temperature (28 °C) and standard pressure (1013 mbar). The breakdown strength value is measured ten times and the average is calculated for each breakdown strength test. Both positive and negative DC breakdown strength has been tested in this experiment. Five sets of electrodes that were used in this experiment are sphere-sphere, rod-rod, rod-sphere, sphere-plane, and rod plane. The electrodes are made of conductive material (aluminum enclosed with a nickel coating) and have a specific size in diameter. One of the electrodes (upper part) is connected to the high voltage source and the other one (lower part) is grounded. The distance of the electrodes can be varied from 0.5 cm to 3.0 cm. The breakdown voltages are determined once the electric current break through the air insulation medium.

The circuit configuration of the HVDC test set-up is shown in Figure 3(a). Both end-side of the primary winding is connected to Control Panel. A high voltage transformer with one end of earth HV winding is connected to the rectifier in series. The smoothing capacitor, measuring resistor and measuring spark gap is connected in parallel. An insulating rod is connected between two rectifiers to make sure both rectifiers are connected in series. This rectifier transforms AC input into DC form. The capacitor is used to reduce the ripple factor effect and smooth the waveform produced after voltage flow through a rectifier. An earth switch is connected to a smoothing capacitor to discharge the stored voltage when the supply is disconnected. The voltage that appears on Control Desk is the breakdown strength that occurs at measuring the spark gap. The Control Desk already set and calculate the breakdown strength of measuring spark gap by measuring the voltage at the measuring resistor. The concept that has been used to determine breakdown strength is a voltage divider. The real set-up diagram is shown in Figure 3(b).



(a)



(b)

Figure 3: Circuit configuration of HVDC test set-up

2.2 FEMM 4.0 Software Simulation

The FEMM 4.0 software is used to simulate the electric field pattern and value. First, set the problem as Electrostatic Problem. Next, enter the coordinate and connect the dot by putting a suitable line and curve. After that, set the material. Then, set the boundary of an electrode where one is High Voltage and the other one is ground. Lastly, set the arc segment and do the mesh and analysis of the design of the electrode pair. These steps are repeated for different electrode pairs and air gap distances.

3. Results and Discussion

The results and discussion were obtained from the experiment and simulation of FEMM 4.0 software to attain the objectives.

3.1 DC Breakdown Strength

The breakdown strength value obtained from the experiment process can be found in Tables 1 and 2, respectively. From Tables 1 and 2, the sphere-sphere electrode pair has the highest breakdown strength of air, followed by the sphere-plane electrode, rod-rod electrode, rod-sphere electrode, and rod-plane regardless of air gap distance for both positive and negative DC breakdown. The value of breakdown strength of the sphere-sphere electrode at 3.0 cm is 73.52 kV and 69.24 kV for positive and negative DC breakdown.

The positive DC breakdown strength value of the sphere-sphere electrode and rod-rod is higher than the negative DC breakdown strength. However, the difference between the negative and positive DC breakdown of the sphere-sphere electrode and the rod-rod electrode is less than 5%. Meanwhile, the positive DC breakdown strength value of rod-sphere, sphere plane, and rod-plane electrodes is lower than the negative DC breakdown strength. There is a huge difference between the positive and negative

DC breakdown of rod-sphere, sphere plane, and rod-plane electrodes for 3.0 cm air gap distance, which is up to 36%, 23%, and 63%, respectively. For all electrode pairs, the difference between positive and negative DC breakdown becomes bigger as the air gap distance is increased.

Table 1: DC breakdown strength of air for both positive DC

Air gap distance, d (cm)	DC breakdown strength of air, U (kV)				
	Sphere-sphere	Rod-rod	Rod-sphere	Sphere-plane	Rod-plane
0.5	20.31	18.74	17.62	19.10	15.74
1.0	32.60	28.05	23.33	32.18	20.10
1.5	46.05	30.27	28.32	43.25	23.62
2.0	57.41	34.89	31.92	51.72	26.64
2.5	65.41	37.99	34.83	59.30	29.45
3.0	73.52	41.90	38.76	51.44	31.85

Table 2: DC breakdown strength of air for both negative DC

Air gap distance, d (cm)	DC breakdown strength of air, U (kV)				
	Sphere-sphere	Rod-rod	Rod-sphere	Sphere-plane	Rod-plane
0.5	20.37	18.07	17.34	18.92	15.36
1.0	31.96	26.17	22.99	32.01	20.58
1.5	44.82	30.66	31.42	42.63	26.66
2.0	54.61	35.23	39.79	51.78	34.19
2.5	64.80	38.78	46.54	56.48	42.82
3.0	69.24	40.69	52.71	63.40	52.06

The characteristic of DC breakdown strength due to different air gap distances of electrodes are shown in Figures 4 and 5. Figures 4 and 5 show the graph of DC breakdown voltage versus air gap distance of the electrode for both positive and negative DC breakdown, respectively. The slopes show the linear regression of the breakdown strength while the point shows the breakdown strength obtained from the experiment. Some of the breakdown voltage obtained is not touching the regression line due to some reason. During the experimental process, there might have been a slight change in temperature, pressure, or humidity of the air that have been affect the breakdown strength due to changes in the weather during the experiment. Since breakdown strength has been affected, therefore the E_{max} value and field utilization factor also might be affected.

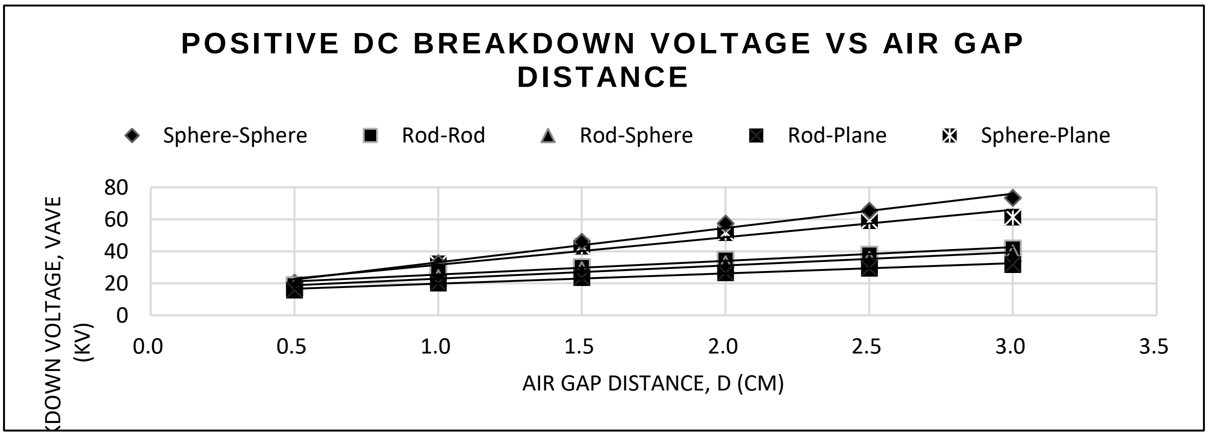


Figure 4: Graph of breakdown voltage versus air gap distance for positive DC

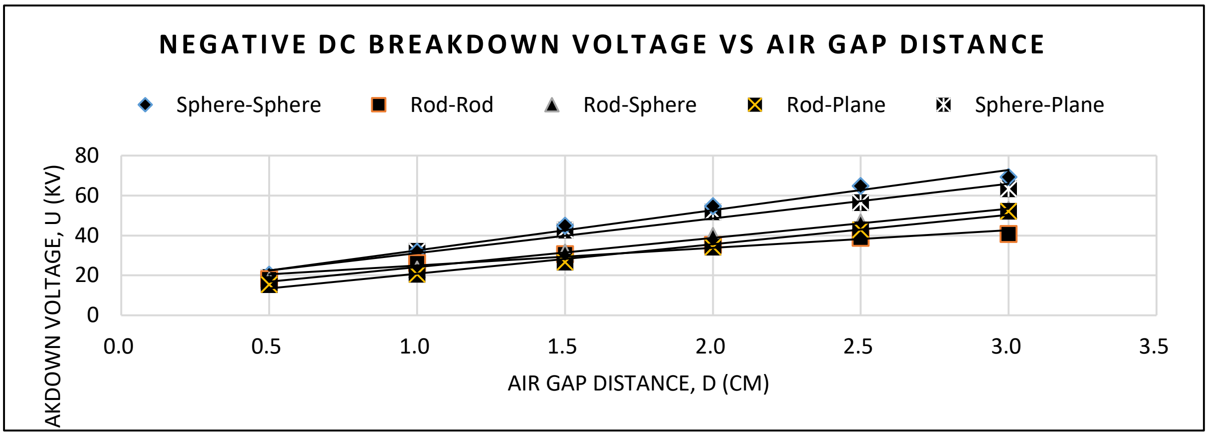


Figure 5: Graph of breakdown voltage versus air gap distance for negative DC

From the results obtained, the breakdown voltage for positive and negative DC breakdown is almost linear, and the breakdown voltage increases as the air gap distance are increased. For both positive and negative DC breakdown, the sphere-sphere electrode pair has a higher gradient, followed by the sphere-plane electrode, rod-rod electrode, rod-sphere electrode, and rod-plane electrode. However, the positive DC breakdown for the sphere-sphere electrode and rod-rod electrode has a higher gradient than their negative DC breakdown. For the rod-sphere electrode, sphere-plane electrode, and rod-plane electrode, the positive DC breakdown has a lower gradient than their negative DC breakdown. The spherical electrodes have higher DC breakdown than rod electrodes and they are near to their type for both positive and negative DC breakdown.

3.2 Electric Field Intensity

Figures 6 to 10 show the electric field pattern for each electrode pair. The figure has then been enlarged to focus on the area of maximum field intensity. The darker color shows the higher intensity of the electric field. From Figures 6 and 9, the electric field pattern of spherical electrodes has a more uniform electric intensity compared to rod and plane electrodes. It is because spheres have a smaller surface area than other shapes due to edgeless and uniform surface area, which influences the electric field intensity. The electric field intensity of the rod electrode is high at the edge of the rod, as shown in Figures 7, 8, and 10.

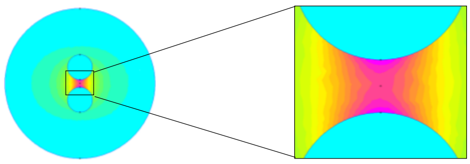


Figure 6: Electric field pattern of sphere-sphere electrode pair

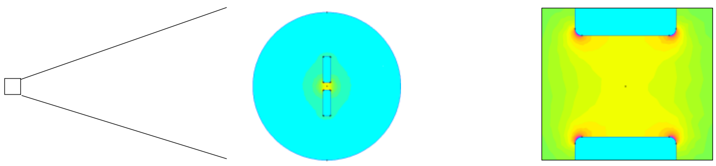


Figure 7: Electric field pattern of rod-rod electrode pair

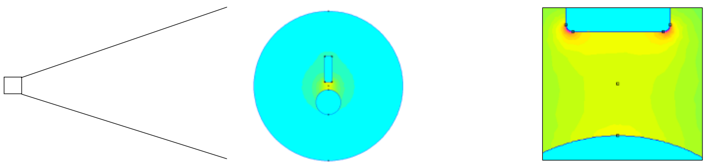


Figure 8: Electric field pattern of rod-sphere electrode pair

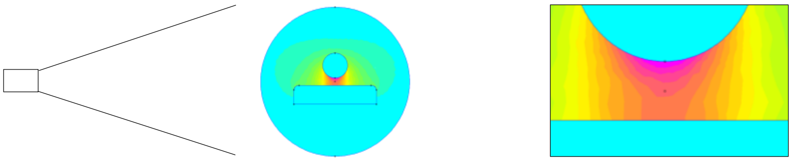


Figure 9: Electric field pattern of sphere-plane electrode pair

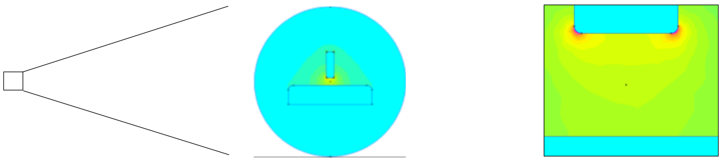


Figure 10: Electric field pattern of rod-plane electrode pair

3.3 Maximum Electric Field

The maximum electric field, E_{max} value during the positive and negative DC breakdown is shown in Tables 3 and 4, respectively. As a result, the maximum electric field is decreased as the air gap distance is increased for all electrode pairs during both positive and negative DC breakdown. During positive DC breakdown at 3.0 cm air gap distance, the lowest maximum electric field value occurred at the sphere-plane electrode (27.866 kV/cm), followed by the sphere electrode, rod-sphere electrode, rod-rod electrode and rod-plane electrode pair.

Table 3: Maximum electric field, E_{max} value during positive DC breakdown

Air gap distance, *d* (cm)	Maximum electric field, E_{max} (kV)				
	Sphere-sphere	Rod-rod	Rod-sphere	Sphere-plane	Rod-plane
0.5	41.632	56.771	54.084	40.457	58.011
1.0	34.591	47.719	45.645	36.122	46.101
1.5	33.554	42.327	42.554	34.215	41.609
2.0	32.346	40.135	39.432	32.257	38.769
2.5	30.322	37.624	37.187	30.945	37.293
3.0	29.186	36.900	36.570	27.866	36.037

Table 4: Maximum electric field, E_{max} value during negative DC breakdown

Air gap distance, *d* (cm)	Maximum electric field, E_{max} (kV)				
	Sphere-sphere	Rod-rod	Rod-sphere	Sphere-plane	Rod-plane
0.5	41.749	54.736	53.225	40.084	56.607
1.0	33.914	48.624	44.985	35.928	47.181
1.5	32.663	42.885	42.126	33.723	44.177
2.0	31.643	40.531	39.343	32.296	40.753
2.5	30.035	38.405	38.448	29.473	39.477
3.0	27.488	35.833	36.946	28.754	37.555

However, during negative DC breakdown at a 3.0 cm air gap distance, sphere-sphere has the lowest maximum electric field value which is 27.488 kV/cm followed by the sphere-plane electrode, rod-sphere electrode, rod-rod electrode and rod plane electrode. The E_{max} value during negative DC breakdown is higher than during positive DC breakdown. For all electrode pairs, there is the least difference between the E_{max} value during positive and negative DC breakdown, which is that the difference between E_{max} value during positive and negative DC breakdown is less than 6% regardless of the air gap distance of the electrode.

3.4 Relationship between E_{max} and Air Gap Distance

Figures 11 and 12 present the graph of E_{max} versus air gap distance for positive and negative DC voltage. From Figures 11 and 12, the relationship between E_{max} and air gap distance during both positive and negative DC breakdown is inversely proportional. During positive DC breakdown, the rod-plane electrode has the highest gradient against air gap distance, followed by the rod-rod electrode, rod-sphere electrode, sphere-plane electrode and sphere-sphere electrode pairs. However, during negative DC breakdown, the rod-plane electrode has the highest gradient against air gap distance, followed by the rod-rod electrode, rod-sphere electrode, sphere-sphere electrode and sphere-plane electrode pairs as shown in Figure 10. From 0.5 cm to 3.0 cm air gap distance, the gradient of E_{max} during positive DC breakdown is greater than during negative DC breakdown. The slopes of linear regression of rod-rod, rod-sphere and rod plane are close to each due to the same electrode used at a high voltage supply.

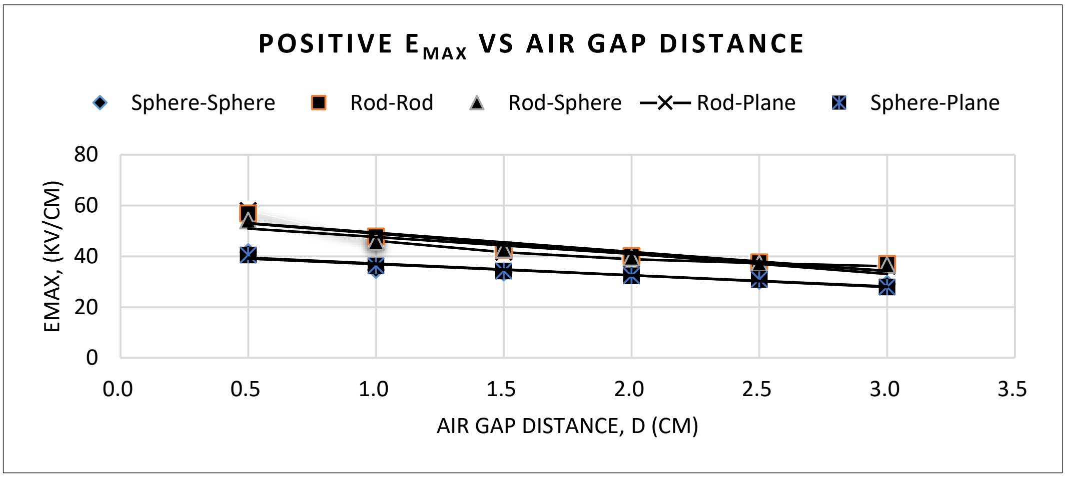


Figure 11: Graph of E_{max} versus air gap distance for positive DC

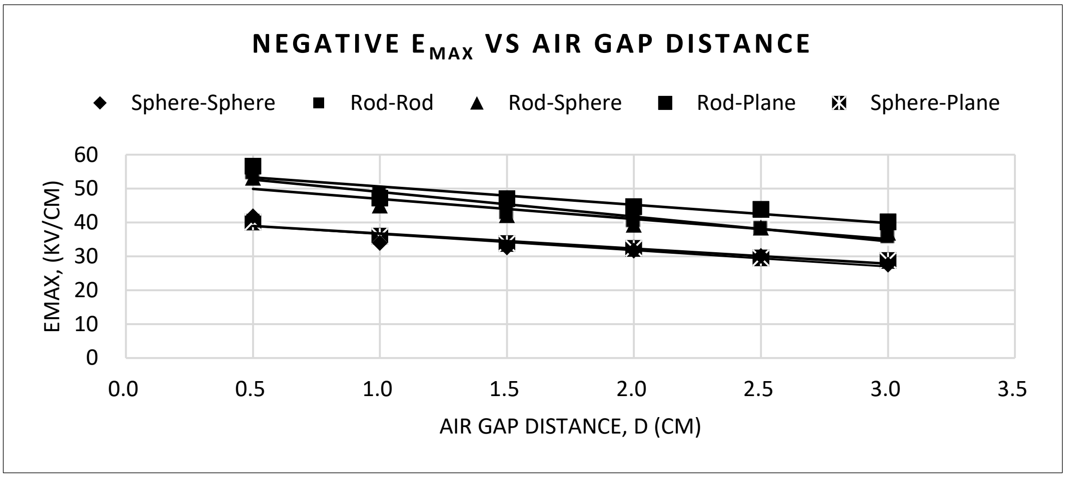


Figure 12: Graph of E_{max} versus air gap distance for negative DC

3.5 Relationship between E_{max} and Breakdown Strength

The relationship between E_{max} and breakdown voltage for positive and negative DC breakdown is shown in Figures 13 and 14, respectively. The E_{max} and breakdown voltage in the graph was placed at the same air gap distance with the same electrode pair. From left to right, the air gap is starting at 0.5 cm till 3.0 cm. By focusing on the relationship between E_{max} and breakdown strength of the sphere-sphere electrode pair in Figure 13, the value is 41.632 kV/cm when the breakdown voltage is 20.314kV at a 0.5 ca m air gap distance. At a 2.0 cm air gap distance, the E_{max} value is 32.35 kV/cm when the breakdown voltage is 57.41 kV. Meanwhile, at a 3.0 cm air gap distance, the E_{max} value is 29.19 kV/cm when the breakdown voltage is 75.80 kV. From here, the E_{max} value is decrease when breakdown voltage and air gap distance were increased which can be relate to the electric field equation where $E = \frac{-V}{d}$ where E is the electric field, V is potential differences or voltage, and d is distance between parallel metal plate.

The negative sign of voltage is showing the direction of decreasing electrical potential. The negative sign can be ignored during the calculation. There is a huge similarity in the relationship between E_{max} and the breakdown strength of positive and negative DC.

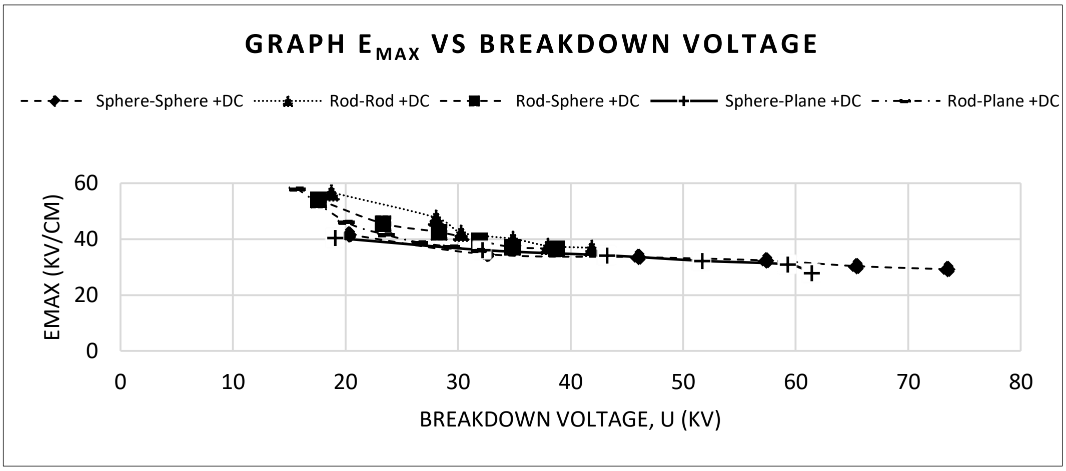


Figure 13: Graph of E_{max} versus breakdown voltage for positive DC

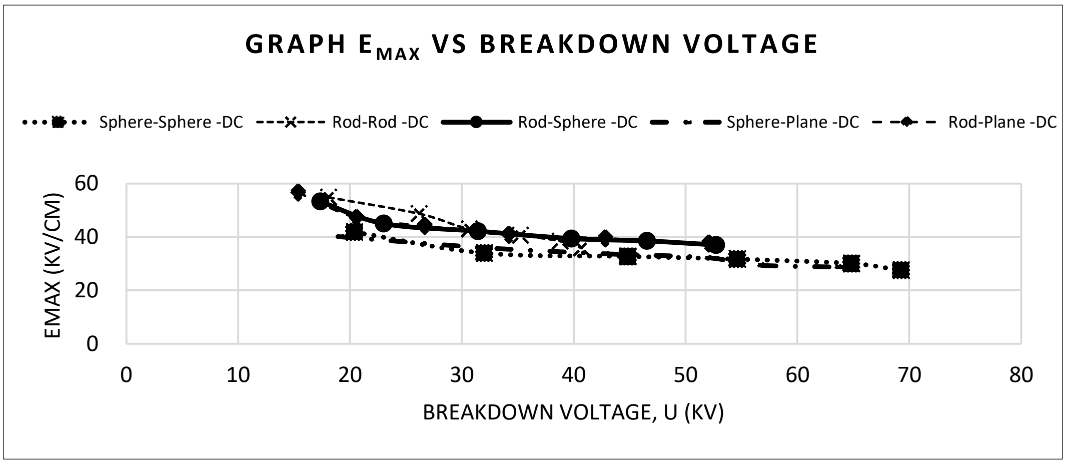


Figure 14: Graph of E_{max} versus breakdown voltage for negative DC

3.6 Relationship between Field Utilization Factor and Air Gap Distance

The result of E_{ave} and ɳ is shown in Tables 5 and 6 during both positive and negative DC breakdowns, respectively. By referring to Tables 5 and 6, the field utilization factor is decreased when the air gap distance is increased during positive DC breakdown for all five pairs of electrodes. The field utilization factor value for positive DC breakdown is almost the same as the field utilization factor value for negative DC breakdown, except for the rod-sphere electrode and rod-plane electrode pair. The highest field utilization factor was obtained by the sphere-sphere electrode pair, which is 0.98 during both positive and negative DC breakdown. The spherical electrode has a uniform surface with a smaller surface area which will affect the value of ɳ.

Figure 15 and 16 shows the graph of field utilization factor versus air gap distance for positive and negative DC, respectively. By referring to Figure 15, the slope of the field utilization factor is most likely negative linear for all electrode pairs, especially sphere-plane electrode and rod-plane. However, for negative DC, only the sphere-plane electrode and rod-rod electrode share the negative linear slope as positive DC. The slope of the sphere-sphere electrode, rod-rod electrode and rod-sphere electrode pairs seem to be slightly unstable.

Table 5: Result of E_{ave}, and η during positive DC breakdown

Air gap distance, d (cm)	Sphere-sphere		Rod-rod		Rod-sphere		Sphere-plane		Rod-plane	
	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η
0.5	40.63	0.98	37.47	0.66	35.25	0.65	38.19	0.94	31.48	0.54
1.0	32.59	0.94	28.05	0.59	23.33	0.51	32.18	0.89	20.10	0.44
1.5	30.70	0.91	20.18	0.48	18.88	0.44	28.83	0.84	15.74	0.38
2.0	28.70	0.89	17.45	0.43	15.96	0.40	25.86	0.80	13.32	0.34
2.5	26.17	0.86	15.19	0.40	13.93	0.37	23.72	0.77	11.78	0.32
3.0	25.26	0.87	13.97	0.39	12.92	0.35	20.48	0.74	10.62	0.29

Table 6: Result of E_{ave}, and η during negative DC breakdown

Air gap distance, d (cm)	Sphere-sphere		Rod-rod		Rod-sphere		Sphere-plane		Rod-plane	
	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η	E_{ave} (kV/cm)	η
0.5	40.74	0.98	36.14	0.66	34.69	0.65	37.84	0.94	30.72	0.54
1.0	31.96	0.94	26.17	0.54	22.99	0.51	32.01	0.89	20.58	0.44
1.5	29.88	0.91	20.44	0.48	20.95	0.50	28.42	0.84	17.77	0.40
2.0	26.31	0.83	17.62	0.44	19.90	0.51	25.89	0.80	17.10	0.42
2.5	25.92	0.86	15.51	0.40	18.62	0.48	22.59	0.77	17.13	0.43
3.0	23.08	0.83	13.56	0.38	17.57	0.48	21.13	0.74	17.35	0.46

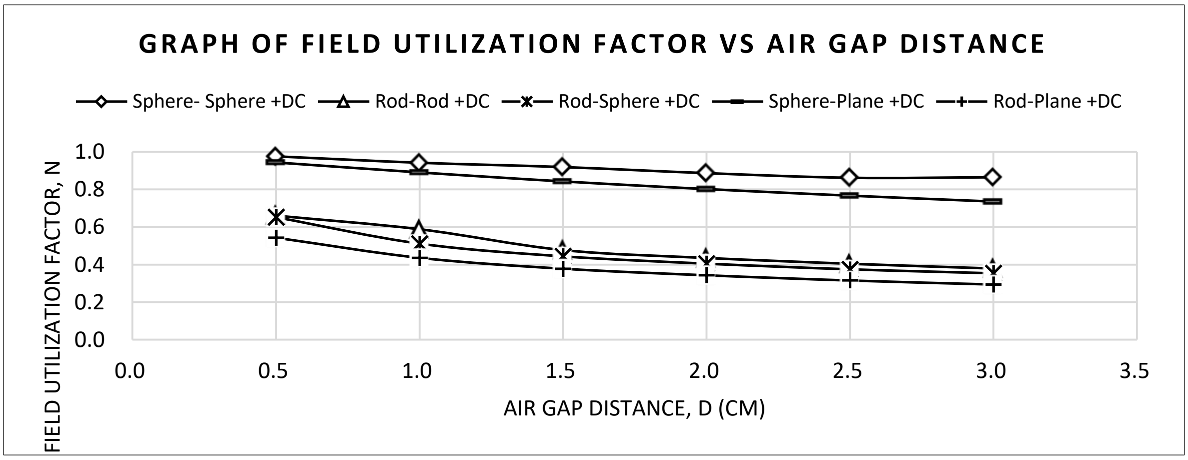


Figure 15: Graph of field utilization factor versus air gap distance for positive DC

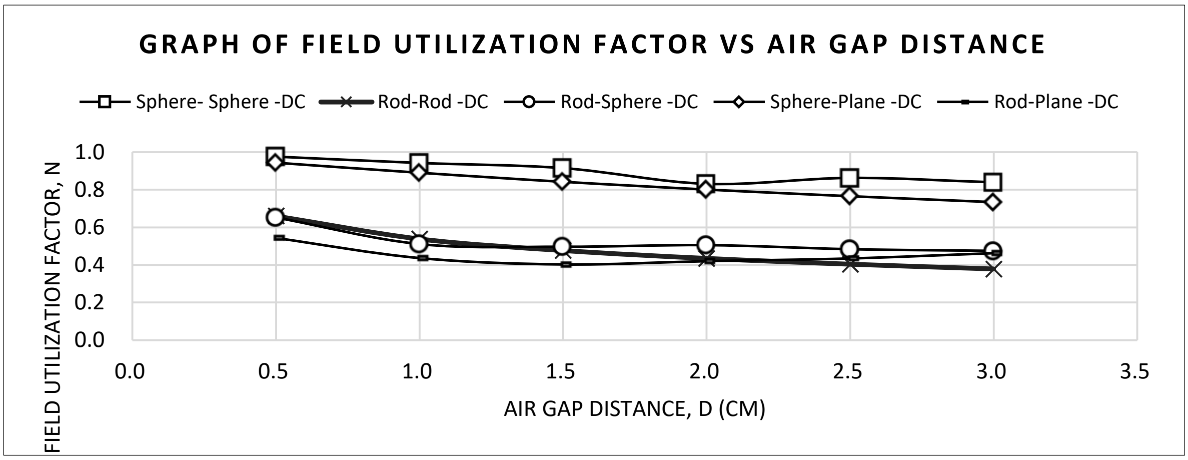


Figure 16: Graph of field utilization factor versus air gap distance for negative DC

4. Conclusion

In conclusion, a sphere-sphere electrode is the best pair compared to the sphere-plane electrode, rod-sphere electrode, rod-rod electrode and rod-plane electrode. It is because the sphere-sphere electrode gives the highest breakdown voltage at any air gap distance. The highest breakdown will produce the lowest E_{max} value. However, the lowest E_{max} value during positive DC breakdown is at 3.0 cm using a sphere-plane electrode pair. The lowest E_{max} will give a high field utilization factor value that does not exceed 1. By referring to Table 4.4, the η value for the sphere-plane at 3.0 cm is 0.74. The difference between positive and negative DC breakdown strength is quite huge, which is 22.08 kV. Even though the sphere-plane electrode for negative DC breakdown does not have the highest value compared to the sphere-sphere, its field utilization factor value is the highest for negative DC breakdown. From here, we can see that the spherical electrode is the most suitable electrode to be used in insulation or protection in high-voltage power systems. The range of field utilization factors obtained from this research is between 0.74 and 1.

Acknowledgement

This research was made possible by funding from a research grant number provided by the Ministry of Higher Education, Malaysia. The authors would also like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

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