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***Research paper***

# Empirical Investigation on Breakdown Characteristics of Air – $CO_2$ Gas Mixtures Under AC and DC Voltages

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**Abstract**

For years there have been countless efforts to find an environmental-friendly gas or gas mixtures to minimize $SF_6$. Researchers have been ongoing to find its alternatives where there are few gasses used to minimize $SF_6$, such as carbon dioxide ($CO_2$) and air. This paper aimed to study the effects of field uniformity towards breakdown characteristic of air-$CO_2$ gas mixtures under AC and DC voltage. Two types of electrodes were used in this experiment which are sphere-sphere electrode (D=5cm) and the rod-rod electrode. Other than that, there are five level of gap distances (0.5cm-2.5cm) with three mixing ratios (100% air–0% $CO_2$, 70% air–30% $CO_2$, 50% air-50% $CO_2$) in 2 bar (abs). The results show the breakdown voltage ($U_{50}$) of the sphere-sphere electrode is higher than the rod-rod electrode under AC and DC voltage. Besides, as the $U_{50}$ goes higher, the $E_{max}$ will be decreasing in any mixing ratio under AC and DC voltage. As for the results, the sphere-sphere electrode is more uniform field than the rod-rod electrode. Moreover, the sphere-sphere electrode has shown the highest withstand capacity of breakdown since they have provided less stress to the field gaps.

***Keywords***: *Air; breakdown voltage; $CO_2$, field utilization factor; maximum electric field.*

## 1. Introduction

Recently, people were concerned about the environmental impact to the world as the result of human activities. From the global environment side, there is an impact of potential climate change due to the increase of greenhouse gases to the atmosphere. In applications, $SF_6$ is considered as a greenhouse gas even though it has been extensively applied in large capacity electric power equipment such as gas-insulated switchgear (GIS) and gas circuit breakers (GCB). According to Kyoto Protocol (COP 3) in 1997, $SF_6$ has been identified as a global warming potential (GWP) with a long lifetime as long as 3400 years [1][2]. The GWP of $SF_6$ is 23900 times that greater than of $CO_2$ [3].

At present, previous researchers have been giving intense efforts to find an environmental-friendly gas such as air [4] and $CO_2$ [5] to substitutes $SF_6$. $CO_2$ is a relatively good interruption performance and much lower GWP than $SF_6$. Besides, $CO_2$ also has a lower boiling temperature than $SF_6$ and remain gaseous at low temperature ranges down to -40℃ at a high gas pressure of 1.0 MPa-abs [6]. In addition, $CO_2$ can be obtained relatively cheaply and is available from must gas manufacture. Although $CO_2$ has a weak electron attaching property, research is carried out as it is an environmental-friendly gas.

On the other hand, air the simplest form of insulator that is used in high voltage application. Although $SF_6$ is regarded as the best gas insulation for high voltage application, air is still widely used to ease maintenance of property.

Researchers have been investigating on mixtures of air and $CO_2$ since these two gases are easy to be found. Martin Seeger reported the results of $CO_2$ measurements are significantly lower compared the results of Cohen in his paper [7]. The results of minimum breakdown electric field strengths are in the range 200 to 300 kV/cm and when the pressure above 2.0 MPa there is no increase of breakdown electric field strength if the lowest values are compared [8]. Zhexin Chen investigated the reduced critical breakdown fields of the hot $CO_2$ and $CO_2$-based mixtures [9]. Hideto Mashidori examined the sparkover characteristics of air-$CO_2$ mixed gases. In his journal, when $CO_2$ concentration increased from 0% to 2%, the sparkover voltage decreased around 20 kV under a positive DC voltage [10]. Although other researchers have been investigating more expensive gasses [11], [12], [13], $CO_2$ and air are still being used as part of the gas mixtures.

This paper aims to investigate the performance of the breakdown voltage ($U_{50}$) and the electric field of $CO_2$ and air in view to minimize $SF_6$ gas as an insulator in high voltage equipment. These gasses will be mixed with three types of mixing ratios and pressure is fixed at 2 bar (abs). Other than that, the electrodes used are sphere-sphere and rod-rod configurations under AC and DC voltages. Perhaps a gas-insulated transmission line (GIL) with $CO_2$ gas mixtures will be able to replace HVDC cable [14] and solve magnetic field problems in overhead transmission lines [15].

## 2. Experimental Setup

All experiments were carried out in a laboratory gas chamber consists of a Plexiglass cylinder fixed with top and bottom flanges which are connected to high voltage and ground potential respectively. The tests were performed in two types of electrode configurations which are sphere-sphere configuration (D-5cm) and rod-rod configurations. Three type of mixtures ratios of air and $CO_2$ are used which are 100% air–0% $CO_2$, 70% air–30% $CO_2$ and 50% air-50% $CO_2$. The tests only focus in two types of voltages, which are: (1) AC ($U_{rms}$) rated up to 100kV; (2) DC rated up to 140kV. The gap distance is adjusted in five level 0.5, 1, 1.5, 2, 2.5 (cm) under the gas pressure of 2 bar (abs). The surfaces of the spheres are polished before starting with several breakdown initiated to remove any dust particles. In addition, FEMM software is used to show the electric field stress around the electrodes. FEMM software also able to show the magnitude of the electric field and solve the complex finite element analysis depends on electrode configurations. The test circuit as shown in Figure 1.

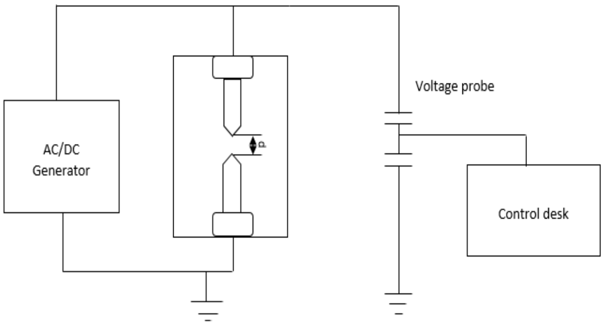



**Fig 1:** Test circuit for AC and DC

### 2.1. Electrode Configurations

There are two electrode configurations used in this experiment which sphere-sphere and rod-rod configurations. The diameter for sphere is 5cm while rod has a tip radius of 0.1cm. Figure 2 shows both of the electrode configurations.

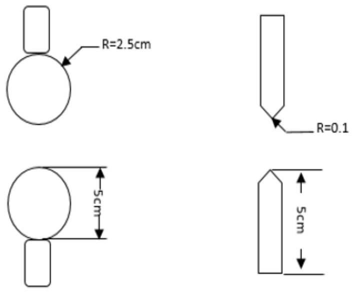



**Fig 2:** Electrode configurations. a) Sphere-sphere b) Rod-rod

### 2.2. 50% breakdown voltage ($U_{50}$)

Based on the Standard [16], the $U_{50}$ is a breakdown voltage by applying 20 shots at a timed interval of 120 seconds

### 2.3. The simulated models

Simulation techniques are carried out to obtain the maximum electric field, $E_{max}$ as in [17], and field utilization factor, η for each electrodes configuration [18]. The field utilization factor is calculated using equation:

$$\eta = E_{mean}/E_{max} \quad (1)$$

While, $E_{max}$ is a maximum electric field for each electrode configuration, simulated using Finite Element Method Magnetics (FEMM) as shown in Figure 3. $E_{mean}$ can be defined as:

$$E_{mean} = v/d \quad (2)$$

Where d is the gap distance between electrodes while v is the applied voltage, which is similar to $U_{50}$ obtained in laboratory works.

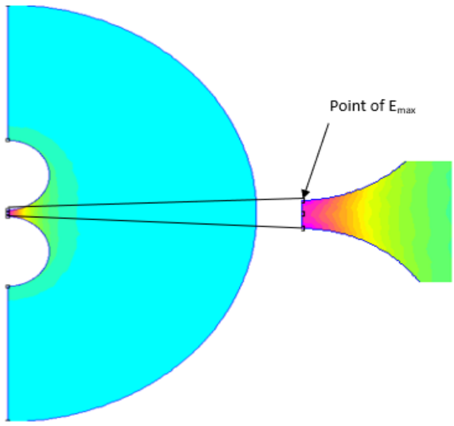


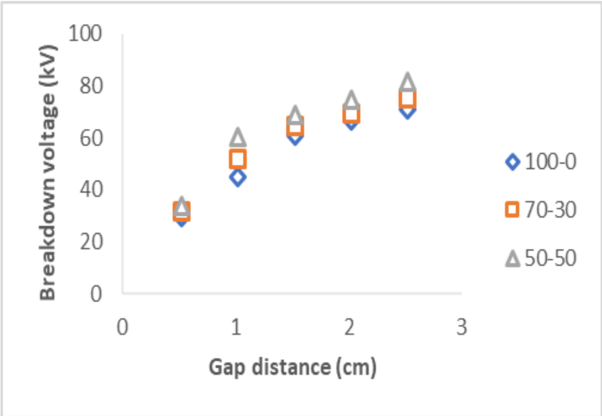

**Fig 3:** Maximum electric field of sphere-sphere configuration

## 3. Experimental Results

This section describes the results obtained with the sphere-sphere and rod-rod configurations under AC and DC voltages. First results are about sphere-sphere configuration which is focuses on $U_{50}$, maximum electric field, $E_{max}$ and field utilization factor, η. Then followed by rod-rod configuration with same focusing.

### 3.1 Sphere-sphere configuration

Figure 4 shows the same approximately increasing trend with an increase of gap distance for both AC and DC voltage. The biggest gap distance in this experiment is 2.5cm while the lowest is 0.5cm. The $U_{50}$ of 50% air-50% $CO_2$ is highest while second highest is a 70% air–30% $CO_2$ where the difference between both mixtures is 2% to 5%. When the tests were carried out with pure air which is 100% air–0% $CO_2$, the $U_{50}$ dropped 12%. In this sphere-sphere, the $U_{50}$ for AC is lower than the DC voltage. The trend of this figure is similar with researcher F. Sadaoui [19]. As mentioned, the $U_{50}$ of 5 level gap distance of AC for 100% air–0% $CO_2$ is 30.64–72.20 kV, 70% air–30% $CO_2$ is 32.91–81.18 kV and 50% air-50% $CO_2$ is 34.77–82.55 kV. For the DC voltage, 100% air–0% $CO_2$ is 31.62–102.51 kV, 70% air–30% $CO_2$ is 35.1–106.36 kV and 50% air- 50% $CO_2$ is 39.88–114.5 kV. The results show the $U_{50}$ of insulating medium are strongly depend upon the electrode configurations.

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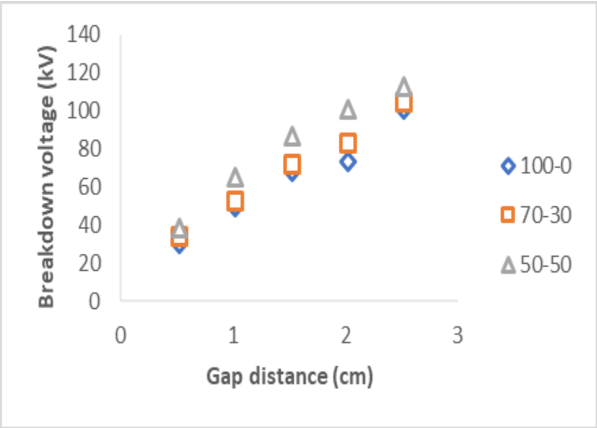
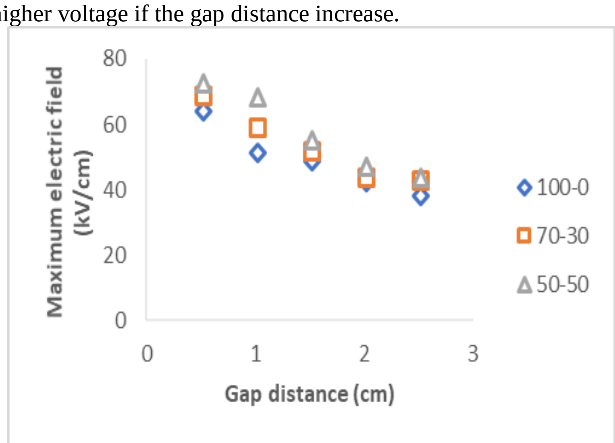



b)

**Fig 4:** Breakdown voltage against gap distance. a) AC, b) DC

By referring to the Figure 5, the maximum electric field, $E_{max}$ decreases when the gap distance increases for the three of different mixtures in AC and DC voltage. In fact, when the electrodes are in uniform field approaching 1, the gap distance increase, the breakdown voltage also increase while the $E_{max}$ will be decreasing. $E_{max}$ for 50% air-50% $CO_2$ is lowest than 70% air–30% $CO_2$ and 100% air–0% $CO_2$ in gap distance for both voltages. Apart from that, the graph also shows the $E_{max}$ of DC voltage is lower than the AC voltage where for gap distance 2.5cm, 50% air–50% $CO_2$ is 61.50 kV/cm while AC voltage is 43.61 kV/cm with a difference is 28%. It shows the sphere-sphere configuration can withstand higher voltage if the gap distance increase.

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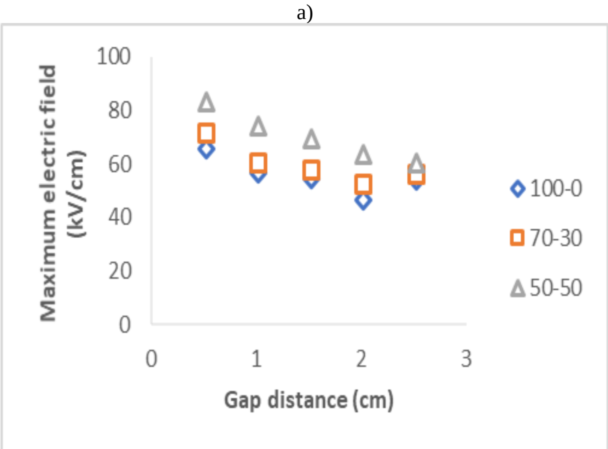
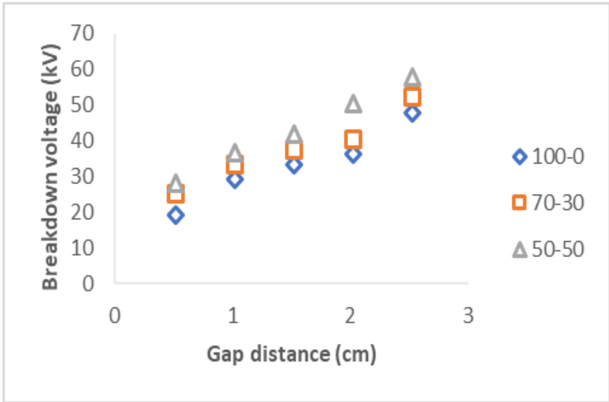



b)

**Fig 5:** Maximum electric field against gap distance. a) AC, b) DC

### 3.2. Rod-rod configuration

Based on the Figure 6, the pattern of $U_{50}$ rod-rod configuration is similar to a $U_{50}$ of sphere-sphere configuration. The difference between these two configurations is about 34%, where lower voltages are obtained with rod-rod configuration. This happened due to rod-rod configuration only required less voltage to reach its breakdown. Rod-rod configuration has a smaller tip radius, and hence higher electric field with the same voltage as compared with sphere-sphere configuration. Hence, lower voltage is required for breakdown to happen. The $U_{50}$ for AC is lower than DC voltage but the result not much different. In 5 level gap distance, the $U_{50}$ of AC is 100% air–0% $CO_2$, 20.1–48.53 kV, 70% air–30% $CO_2$ is 25.96–53.22 kV and 50% air-50% $CO_2$ is 28.9–58.88 kV. For the DC voltage, 100% air–0% $CO_2$ is 24.72–53.31 kV, 70% air–30% $CO_2$ is 28.62–56.95 kV and 50% air-50% $CO_2$ is 32.95–60.28 kV. Therefore, the difference of breakdown between AC and DC is around 10%.

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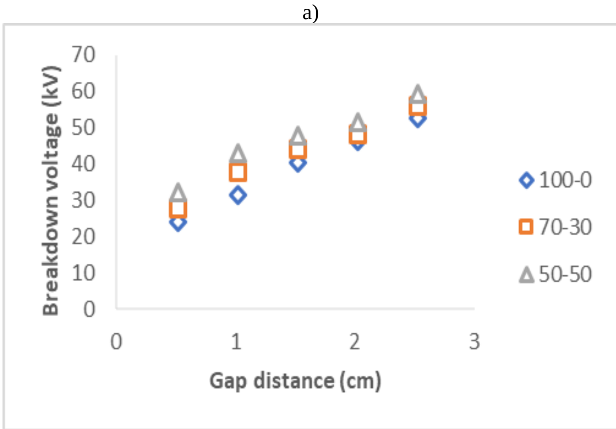
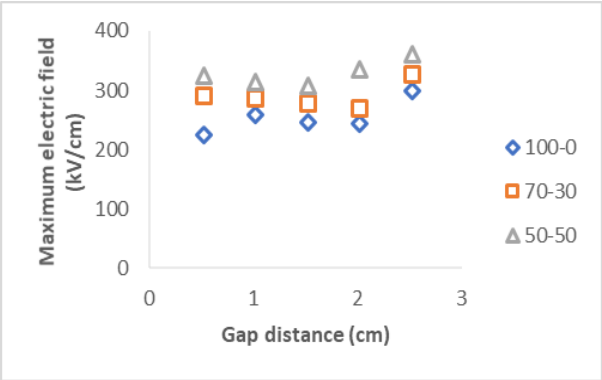



b)

**Fig 6:** Breakdown voltage against gap distance. a) AC, b) DC

Figure 7 shows the $E_{max}$ for AC and DC voltage of rod-rod configuration. It is different with sphere-sphere configuration where $E_{max}$ is higher due to the geometry of the electrode. Even though the rod-rod configuration is a symmetric arrangement, the $E_{max}$ between the rods is much more non-uniform than in the sphere-sphere configuration. The other reason was found that $E_{max}$ produced by uniform fields is lower than the non-uniform field. This is because the lines of the electric field is more spread out towards a weaker electric field. In addition, the other reason is about that $E_{max}$ could be caused by the space charge where a uniform field with a space charge may not remain uniform ideally [20]. Breakdown voltage of AC for 100% air–0% $CO_2$ is 228.55–302.40 kV/cm, 70% air–30% $CO_2$ is 295.19–331.62 kV/cm and 50% air-50% $CO_2$ is 328.62–365.02 kV/cm. For the DC voltage, 100% air–0% $CO_2$ is 281.09–332.18 kV/cm, 70% air–30% $CO_2$ is 325.43–354.86 kV/cm and 50% air-50% $CO_2$ is 374.67–375.61 kV/cm. The graph also shows the value of $E_{max}$ of 50% air-50% $CO_2$ and 70% air–30% $CO_2$ decrease at first fourth gap distance but on 2.5cm the value increase while for 100% air–0% $CO_2$ linearly increase without dropped at any gap distance.

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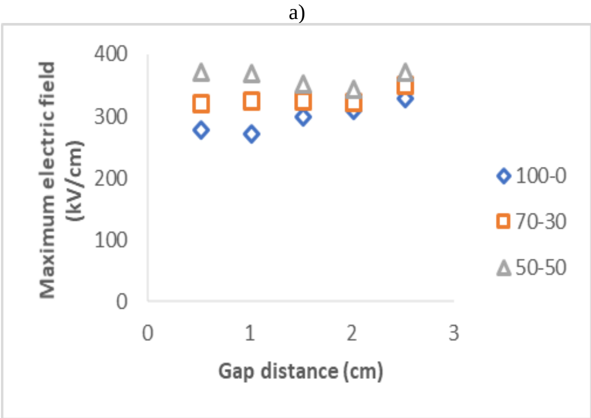
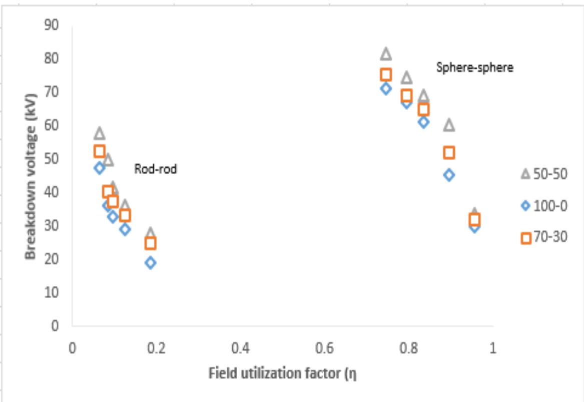



b)

**Fig 7:** Maximum electric field against gap distance. a) AC, b) DC

### 3.3. Field utilization factor under AC and DC

Figure 8 illustrates the field utilization factor of AC and DC for sphere-sphere and the rod-rod configuration. It shows that the non-uniform field contributes to higher $E_{max}$ which provided lower breakdown voltages for all mixtures. In theory, the higher of field utilization factor will be providing the higher of $U_{50}$. In this experiment, for a certain electrode pairs, the $U_{50}$ decreases with increment of field utilization factor. This is due to the fact that when the gap distance between the electrodes gets higher, the field uniformity will become lesser, and hence lower field utilization factor. As the result, since gap distance increases, $U_{50}$ will also increase. The figure also shows that sphere-sphere electrode configuration provide higher field utilization factor, which is more uniform as compared to rod-rod electrode configuration. This is the reason why IEC has adopted sphere gaps as a calibration device since it has given more uniform field and linearity is maintained even the gap distance is increasing [16]. Plus, the rod-rod configuration are not allowed to be used as measuring devices because of the large scatter of distructive discharge voltage and also strong influence of the humidity [21].

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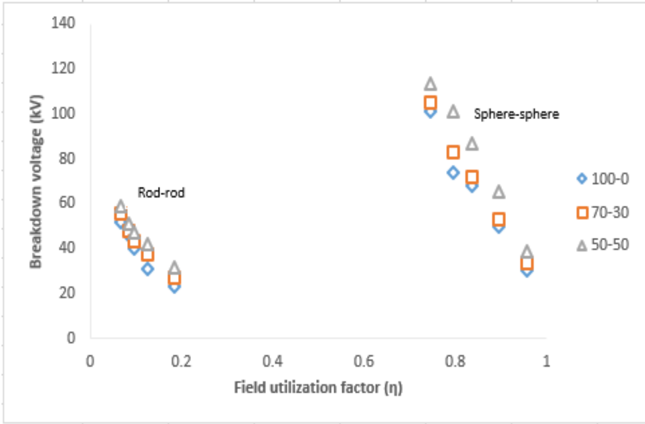


b)

**Fig 8:** Breakdown voltage against field utilization factor of sphere-sphere and rod-rod a) AC, b) DC

## 4. Conclusion

The goal of this work is to investigate the breakdown voltage ($U_{50}$) and the electric field of air-$CO_2$ with three types of mixtures ratio under AC and DC voltage. The gas pressure is fixed at 2 bar (abs). Two different electrode configurations with 5 level of gap distances were used to provide a different uniformities field. The electric field acquired from $U_{50}$ and simulated using finite element methods. It appears that the $U_{50}$ of the DC voltage is higher than the AC voltage. In addition, the breakdown voltage of the sphere-sphere electrode is higher than the rod-rod electrode in all gap distance and mixing ratio. In other words, $U_{50}$ is affected by variation in gap length and mixing ratio which is when the gap distances and mixing ratio increase, the breakdown voltage will be increasing. By comparing these mixing ratios, the highest $U_{50}$ was discovered by 50% air-50% $CO_2$, second is 70% air–30% $CO_2$ and followed by 100% air-0% $CO_2$. The pure air was the lowest $U_{50}$ for all the time. The distributions of the $E_{max}$ are strongly affected by the gap distance and mixing ratio. The $E_{max}$ of the sphere-sphere electrode is a lower than the rod-rod electrode with a very high field utilization factor value. From the result, the sphere-sphere electrode is more uniform field than the rod-rod electrode. Moreover, the sphere-sphere electrodes have shown the highest withstand capacity of breakdown since they provided less stress to the field gaps.

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