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Investigation on the Breakdown Characteristics of Nitrogen and Oxygen Gas Mixtures Under Standard Lightning Impulse

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Abstract: This paper is concerned about the potential for sulphur hexafluoride (SF_6) to contribute to global warming; therefore, it is necessary to find another gas to replace SF_6 as the gas insulator in high voltage applications. To determine the best gas insulator for insulation properties, the breakdown characteristics of N_2 and O_2 gas mixtures, pure N_2 gas, and pure O_2 gas were analyzed by applying a lightning impulse, varying the gap distance between the sphere and plate electrodes, and varying the mixing ratio of these gases at the same pressure (1 bar). Up and Down method is used to measure the breakdown voltage to obtain 50% of the breakdown voltage, U_{50} from breakdown testing according to the BS EN 60060-1 standard. For all gas insulators, U_{50} increases with electrode distance. Simulations from FEMM software show that Emax decreases with electrode gap length. As maximum electric field, Emax decreases, the field utilization factor decreases, showing that electrode configuration uniformity diminishes with gap distance. Based on the results obtained, N_2 gas was discovered to be one of the most effective insulators as a secondary gas compared to O_2 gas and gas mixtures between N_2 and O_2 gas because it has the highest breakdown voltage values, 37.415 kV as compared to 34.123 kV (N_2+ O_2 gas) and 20.730 kV (O_2 gas). Based on this study, pressure variations could be made as insulating properties can be accurately identified by using gas chamber pressure and rising pressure increases gas mixture breakdown strength.

Keywords: Lightning Impulse, N_2 and O_2 gas, Up and Down Method, Breakdown Voltage Test, U_{50}

1. Introduction

Globally, SF_6 is utilized as a GIL and GIS insulating gas due to its efficacy as an exceptional insulating gas [1]. However, SF_6 has influenced the greenhouse effect and global warming, which will have a significant impact on the ecosystem.

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This has led to SF_6 being designated as one of the six prohibited greenhouse gases by the Kyoto Protocol in 1997, limiting its use in electrical applications until 2020 [2]. In addition, SF_6 gas is costly due to its application in gearbox lines. For this reason, SF6 gas should be replaced with other forms of mixed gas that can be used as a healthful alternative insulating gas. Numerous gas combinations, including Trifluoroiodomethane (CF_3I) and Nitrogen (N_2), Sulphur hexafluoride (SF_6) and Nitrogen (N_2), and five-carbon perfluorinated ketone ($C_5F_{10}O$) and Carbon dioxide (CO_2), have been investigated in the past.

The breakdown characteristics of pure N_2, pure O_2 gas, and N_2 + O_2 gas mixtures have been analyzed by conducting breakdown voltage testing in the High Voltage Laboratory and simulating the electric field produced between two electrodes by using Finite Element Magnetic Method (FEMM) software. Sphere and plane electrodes have been used in the gas chamber at the same pressure (1 bar) for each test. So that the relationship between the effect of difference gap distance on breakdown strength and electric field uniformities for all gases can be produced.

2. Materials and Methods

This section describes the experimental setup and simulation works as a measurement method to collect data for the study.

2.1 Materials

The study incorporates the following six specifications and properties of materials, equipment, and resources: The lightning impulse used is positively polarized, with voltages below 140 kV to comply with lab equipment limitations. The gas insulators used include a 50:50 mixture of Nitrogen (N2) and Oxygen (O2), 100% Nitrogen (100:0), and 100% Oxygen (0:100). The tests are conducted at a pressure of 1 bar (abs).

2.2 Experimental Works

2.2.1 Lightning Impulse Generation

An impulse generator that can produce impulses as high as 100kV generates the standard 1.2/50 lightning impulse. For measuring impulse voltage, a capacitive divider with a 50ns rise time was utilized. Other measurement equipment consists of an oscilloscope with digital storage and resistive divider to measure DC output.

2.2.2 Gas Chamber

N_2 and O_2 gas was inserted into the gas chamber based on mixture ratio needed. The plane electrodes are grounded, while the sphere electrodes are connected to high voltage. Line actuators have been used to adjust the bottom electrodes to get different levels for each gap distance in order to keep gas mixtures and pressures inside the gas chamber. The same gas pressure (1 bar) has been applied for each type of electrode configuration.

2.2.3 Electrode Configuration

A sphere-plane electrode configuration was used in this study. 5 cm is the diameter of the sphere electrode, while 9 cm is the diameter of the plane electrode. All electrodes are manufactured from brass. Variable distances between the electrodes; 0.5 cm, 1.0 cm, 1.5 cm, 2.0 cm, and 2.5 cm, have been used to determine the uniformities of each electrode configuration.

2.2.4 Up and Down Method

The breakdown voltage, U_{50}, for every gas insulator was measured using the up-and-down method under lightning impulse. Each data point was tested 20 times. The test started with a low voltage and gradually escalated till breakdown. The test is repeated until a consistent breakdown voltage is reached by decreasing the voltage. Figure 1 depicts the procedure involved.

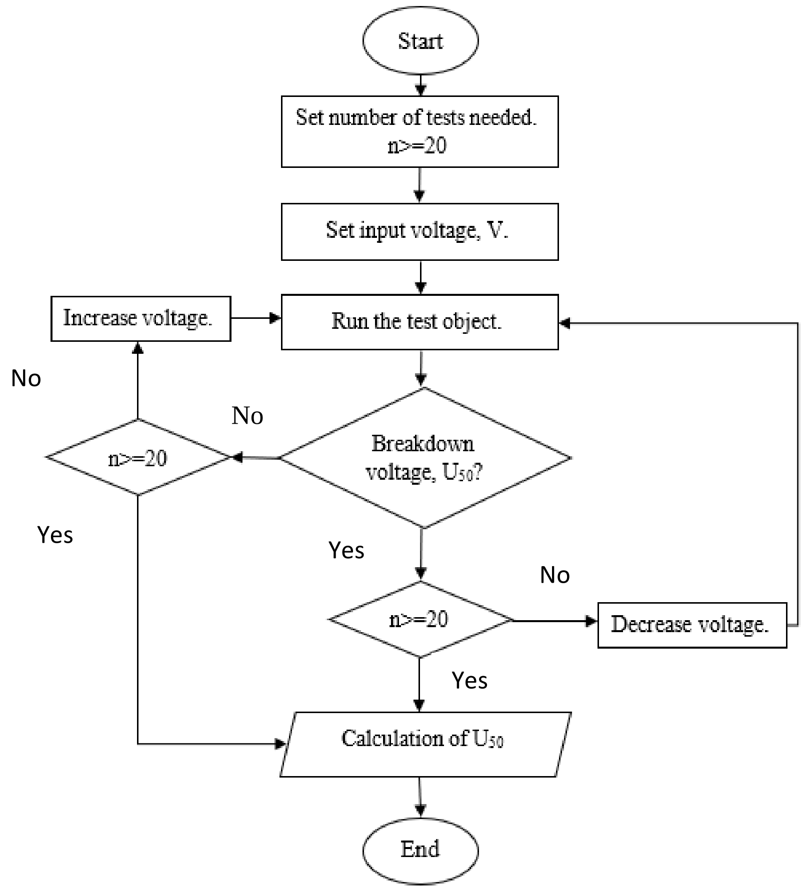

Figure 1: Up and Down method test

2.3 Simulation Works

Finite Element Method Magnetics (FEMM) is utilized for modeling and simulating electric field distribution based on the values of U_{50} obtained from experimental works in the High Voltage Laboratory. Instead of a complete three-dimensional (3D) model, a simplified two-dimensional (2D) model is created. Even though it is a 2D model, the simulation's accuracy will not be affected. By employing this method, memory and processing time will be conserved. Axis-symmetric characteristics are utilized to further minimize the model without impacting the simulation results.

3. Results and Discussion

A. 0 50% of Breakdown Voltage, U_{50}

Comparison between all the gases used has been analyzed based on experimental and simulation data. The values of U_{50} have been tabulated as shown in Table 1, while Figure 2 shows the graph related. It shows that the values of U_{50} of pure nitrogen, N_2 gas for 0.5 cm gap distance, 37.415 kV are greater than those of the others, 20.730 kV (N_2 and O_2) and 34.1225 kV (Pure O_2). N_2 gas has a higher breakdown strength than O_2 gas because it ionizes less. N_2 gas has a lower dielectric constant (1.00054) than O_2 gas (1.00058), indicating that electrical breakdowns are less common with lower dielectric constants [3]. N_2 and O_2 gas mixes and pure O_2 have similar U_{50} values for gap distances between 1.0

cm until 2.5 cm, which is greater than pure N_2. Due to [3], U_{50} of pure N_2 for gap distances between 1.0 cm until 2.5 cm should be higher.

Table 1: U_{50} values for each type of gas insulator

Types of gas insulator	50% of breakdown voltage, kV				
	0.5 cm	1.0 cm	1.5 cm	2.0 cm	2.5 cm
$N_2 + O_2$	20.730	53.643	69.607	78.949	84.04
Pure N_2	37.415	55.335	60.0145	64.7805	71.295
Pure O_2	34.1225	57.834	66.5465	75.8187	88.4295

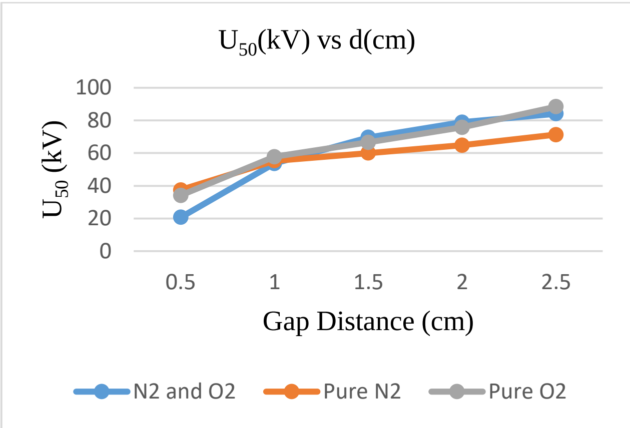

Figure 2: U_{50} vs d for each type of gas insulator

B. Maximum Electric Field, Emax

FEMM software upper bound field intensity simulation calculated the maximum electric values for each gap distance. Table 2 and Figure 3 show that Emax decreases with distance. Paschen's Law states that breakdown electric field is inversely proportional to gap distance [3]. As the electrodes get farther apart, the electric field evenly surrounds the high-voltage electrode, needing a larger voltage to break gas.

Table 2: Emax for each type of gas insulator

Types of gas insulator	Maximum Electric Field, Emax (MV/cm)				
	0.5 cm	1.0 cm	1.5 cm	2.0 cm	2.5 cm
N_2 and O_2	4.69	6.85	6.62	6.19	5.71
Pure N_2	8.47	7.06	5.71	5.08	4.85
Pure O_2	7.72	7.38	6.33	5.94	6.02

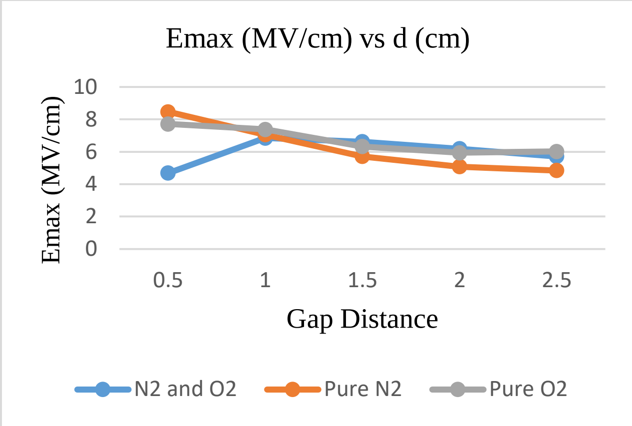

Figure 3: Emax vs d for each type of gas insulator

C. Field Utilization Factor, η

The field utilization factor,η remains consistent across gap distances for each gas insulator. For example, at a 1.5 cm gap distance, η remains constant at 0.701, as shown in Table 3 and Figure 4. Increasing the gap spacing lowers η, achieving the desired outcome. The type of gas used as an insulator does not affect η, but the electrode configurations do. Each configuration has its unique electric field distribution, simulated using FEMM software. From the provided information, it is evident that higher η values lead to a more uniform electrode configuration.

Table 3: η for each type of gas insulator

Types of gas insulator	Field Utilization Factor, η				
	0.5 cm	1.0 cm	1.5 cm	2.0 cm	2.5 cm
N_2 and O_2	0.884	0.783	0.701	0.638	0.589
Pure N_2	0.883	0.784	0.701	0.638	0.588
Pure O_2	0.884	0.783	0.701	0.638	0.588

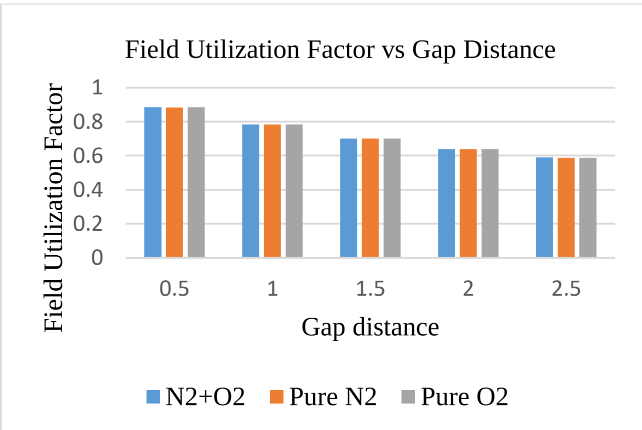

Figure 4: η vs d for each type of gas insulator

4. Conclusion

N_2 gas is found to be a highly effective and economical insulator compared to O_2 gas and gas mixtures containing N_2 and O_2. N_2 is the most used electropositive gaseous dielectric due to its favorable properties. However, when considering different gap distances, pure O_2 exhibits higher breakdown voltage values, suggesting possible inaccuracies in the measurement of the sphere-to-plate electrode distance. As O_2 can decrease the breakdown voltage, it is rarely used as the primary gas insulator. Instead, it is added in specific proportions as a secondary gas to enhance the insulation properties of certain gas mixtures. The strong oxidizing nature of O_2 can have negative effects and destabilize the gas mixture [4]. The breakdown characteristics of the three gas insulators are similar when tested under the same pressure conditions. To further investigate insulation properties, it is necessary to examine different pressure conditions.

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