CHAPTER 1

$N_2 + O_2$ BREAKDOWN CHARACTERISTIC UNDER LIGHTNING IMPULSE WITH NEEDLE-PLANE GAP

*Nuraina Maisarah Nordin[1], Muhammad Saufi Kamarudin[2]**

[1-2]Department of Electrical Engineering,
Faculty of Electrical and Electronics Engineering
University Tun Hussein Onn Malaysia,
86400 Parit Raja, Batu Pahat, Johor, Malaysia.
*Corresponding Email: saufi@uthm.edu.my

1.1 INTRODUCTION

Circuit breakers are essential for protecting electrical power systems by interrupting electric currents during fault conditions [1]. SF_6 gas circuit breakers use Sulphur hexafluoride as an insulating and arc-quenching medium due to its excellent dielectric properties [2]. However, SF_6 is also a potent greenhouse gas with a Global Warming Potential (GWP) 22,800 times greater than CO_2 and can remain in the atmosphere for thousands of years [3]. In Malaysia's Biennial Update Report 3, most SF_6 emissions were linked to electrical equipment, particularly transmission switchgear, reflecting the growing demand for electricity [4]. These environmental concerns have prompted increasing efforts to find suitable alternatives to SF_6 in power systems [3].

1.2 MATERIAL AND METHOD

All in this research, two methodological approaches were employed. The first involves conducting experimental work to collect relevant data for the study. The second approach utilized simulation using Finite Element Method Magnetics (FEMM) to analyze the characteristics of the electric field for three different gas ratio types.

1.2.1 MATERIAL

This study incorporates with the following specifications that are mentioned in Table 1.1 with voltage below 100kV.

Table 1.1: Specification of Material.

Description of material setup	Specification
Types of lightning impulse	Positive polarity
Types of gas mixtures	$O_2 + N_2$
Ratio of gas mixtures ($O_2:N_2$)	30:70, 50:50,70:30
Gas distance, cm	0.5, 1.0, 1.5, 2.0, 2.5
Type of electrode configuration	Needle-plane
Pressure	1 bar

1.2.2 EXPERIMENTAL WORKS

Based on Figure 1.1, the impulse circuit starts using a 230 V AC power supply as the main source. This power is then sent to a step-up transformer (HV9105), where the voltage is increased to a much higher level required for testing. Three types of winding are used in the transformer: the exciter winding, which is connected either in parallel for 220 V or in series for 440 V, the high-voltage winding, which is designed to produce up to 100 kV and the coupler winding, which is provided for cascading multiple transformers. The transformer is protected with special shielding to prevent corona discharge and ensure safe operation. After the voltage is increased, it is measured using a capacitive voltage divider. Then, the AC voltage is converted into DC using several silicon rectifiers. These rectifiers are used to maintain stable voltage and reduce the effects of voltage fluctuations. A charging resistor is added to the circuit to limit the charging rate of the capacitors and to prevent overcharging, which could lead to dangerous voltage levels or damage.

Figure 1.1: Single-stage circuit lightning impulse test setup of TERCO.

Once the capacitors are charged to the required voltage, the charging circuit is disconnected. The stored energy in the capacitors is then discharged through an impulse generator. The discharge is triggered when a high voltage is applied across a sphere gap, causing a spark to jump across it. Through this process, a lightning-like impulse is generated and passed through the test setup. The test is conducted inside a gas chamber that is filled with a mixture of nitrogen and oxygen gases, which serve as insulation. If the voltage exceeds the breakdown level, arcing is produced inside the chamber, indicating a failure of the gas insulation. A grounding switch is included in the system so that the high-voltage parts are automatically grounded when the setup is turned off, ensuring user and equipment safety.

1.2.2.1 FILLING AND REMOVAL OF GAS

As illustrated in Figure 1.2 and Figure 1.3, the process begins by sealing all chamber valves and activating the vacuum pump to evacuate the gas chamber. The evacuation continues until the vacuum gauge indicates a maximum negative pressure (approximately -76 mmHg), confirming minimal residual air. A small amount of air may be briefly introduced to stabilize conditions before testing. This evacuation typically takes 10–20 minutes.

For the gas filling process, valve V3 remains closed while valve V2 is opened to protect the pressure gauge from vacuum exposure. Valve V1 is then opened to connect the vacuum pump to the discharge valve for final evacuation. Once the desired vacuum level is achieved, the chamber is filled with a 50(N_2):50(O_2) gas mixture first by introducing N_2 until the vacuum gauge reads 15 Hg, followed by O_2 until the gauge reaches 1 bar. The gas is left in the chamber overnight to allow any fluctuations in pressure and temperature to stabilize, ensuring that the gas mixture reaches thermal and pressure equilibrium.

Figure 1.2: Process of removing gas from gas chamber using vacuum pump.

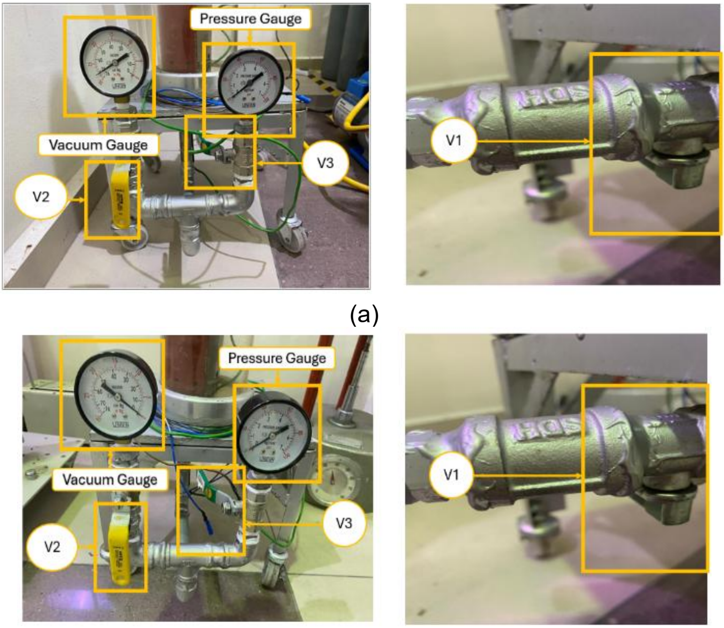
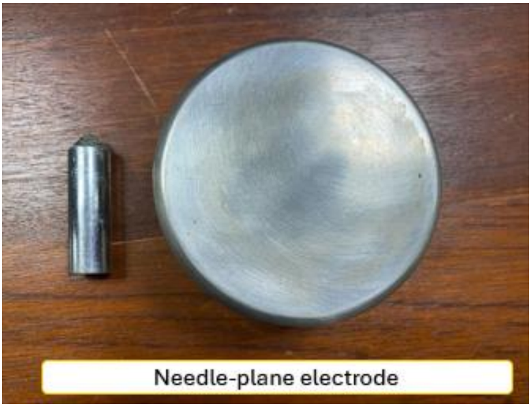


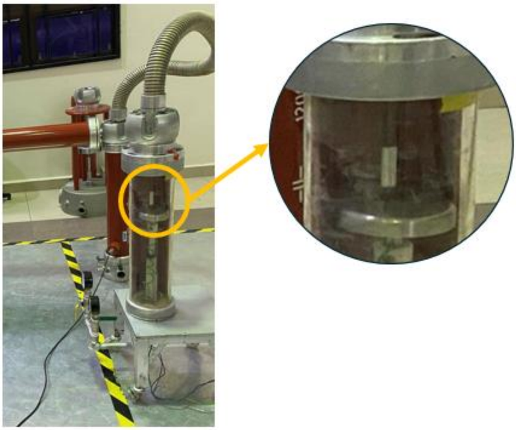
Figure 1.3: (a) Condition of valve when process of removing gas occur; (b) Condition of valve when process of filling gas occurs.

1.2.2.2 GAS CHAMBER

As illustrated in Fig 1.4 (b), nitrogen (N_2) and oxygen (O_2) gases were filled into the gas chamber according to the required mixture ratios. The chamber maintained a constant pressure of 1 bar for all tests. The electrode configuration consisted of a grounded plane electrode and a high-voltage sphere electrode. A linear actuator was used to adjust the bottom electrode, allowing precise variation of the gap distance while preserving the internal gas composition and pressure. This setup enabled reliable measurement of the 50% breakdown voltage (U_{50}) under standardized lightning impulse conditions.



(a)



(b)

Figure 1.4: Needle-plane electrode; (b) Electrode arrangement in gas chamber.

1.2.2.3 UP AND DOWN METHOD

This method systematically determines the 50% breakdown voltage (U_{50}), the voltage level at which breakdown occurs in 50% of applied impulses. A total of 25 impulse tests is conducted per data point under standard lightning impulse conditions. The test begins at a low voltage, increasing incrementally until breakdown occurs the voltage is then reduced and reapplied, cycling until a stable U_{50} value is obtained. Voltage and current data are recorded during each event. This method was applied to three different mixtures of gas ratio types across various electrode gap distances to assess breakdown characteristics.

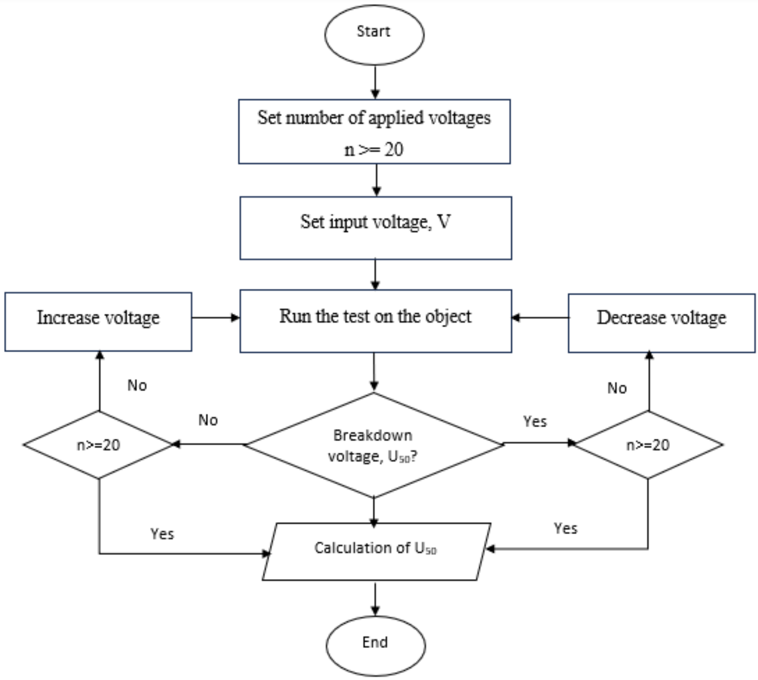


Figure 1.5: Flowchart Up and Down Method.

1.3 SIMULATION WORKS

Finite Element Method Magnetics (FEMM) is employed to model and simulate the electric field distribution based on U_{50} values obtained from experimental tests conducted in the High Voltage Laboratory. To optimize computational efficiency, a two-dimensional (2D) axisymmetric model is used in place of a full three-dimensional (3D) simulation. This simplification significantly reduces memory usage and processing time without compromising the accuracy of the results. The axisymmetric approach effectively captures the electric field behaviour around the needle-plane electrode configuration, ensuring reliable simulation outcomes aligned with experimental conditions.

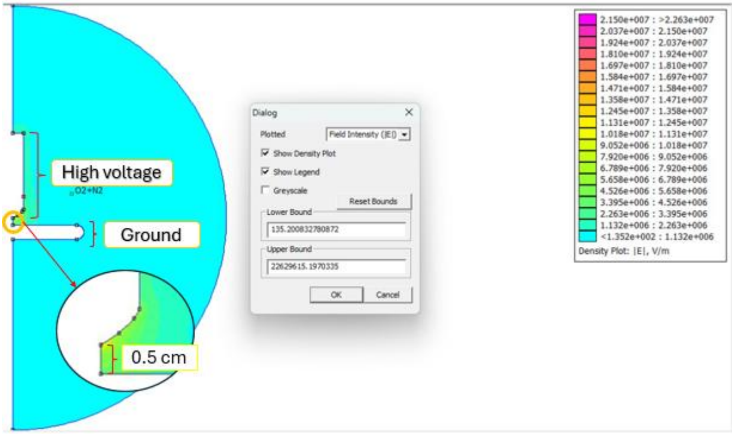


Figure 1.6: Simulation Modeling of Electric Field Distribution.

1.4 RESULTS AND DISCUSSION

1.4.1 BREAKDOWN VOLTAGE AGAINST GAP DISTANCE

According to the Figure 1.7, breakdown voltage rises as the gap separation and O_2 concentration in the O_2 - N_2 mixture increased. Three ratios of 30% O_2:70% N_2, 50% O_2:50% N_2 and 70% O_2:30% N_2 were used in a trial gap width of 0.5 cm to 2.5 cm. In every way, increasing gaps needed more voltage to cause breakdown. Increased oxygen increased performance of insulation, at 0.5 cm the measuring breakdown voltage at 30% of the oxygen concentration was 31.81 kV, and 41.33 kV at 70% concentration of the oxygen. This is because oxygen has the capability of binding the free electrons that prevents ionization unlike nitrogen which contributes to it. The mixture that had the best performance was the 70% O_2 due to the high potential of it being a cleaner alternative to SF_6. These results verify the fact that both the gas ratio and gap distance have prominent impacts on insulation strength in lightning impulse conditions.

Table 1.2: U_{50} values for each gas mixture ratio.

Gas Mixture Ratios of O_2 and N_2	50% Breakdown Voltage, U50 (kV)				
	0.5 cm	1.0 cm	1.5 cm	2.0 cm	2.5 cm
30% + 70%	31.81	40.51	51.52	56.55	65.6
50% + 50%	36.86	49.86	56.45	65.72	69.33
70% + 30%	41.33	56.41	62.87	65.15	75.75

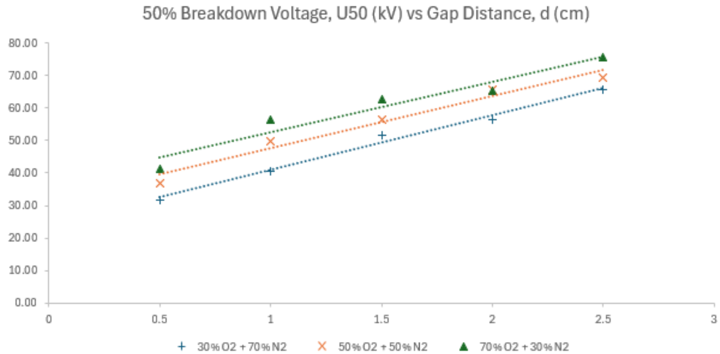


Figure 1.7: U_{50} (kV) breakdown voltage against gap distance (cm) for each type of gas mixtures ratios.

1.4.2 Emax AGAINST GAP DISTANCE

By results obtained in Figure 1.8, it was found that gas mixtures of greater proportion of oxygen always produced stronger electric fields (Emax) at all the gap distances. With a gap of 0.5 cm, the observed output was 2.95×10^7 V/m and 2.26×10^7 V/m Emax of 70% in O_2 with 30% in in N_2 and 30% in O_2 with 70% in N_2 respectively. This has also been observed in bigger gaps with oxygen rich mix still having higher Emax values. High electron affinity of oxygen increases insulating strengths due to resistance to ionization thus the gas can withstand stronger fields. However, the field distribution widens as the gap increases, but Emax nevertheless increases because of higher applied voltage at 2.5 cm, Emax was 2.84×10^7 V/m in 70% in O_2 and 2.47×10^7 V/m at 30% in O_2.

Table 1.3: Maximum electric field values for each gas mixture ratio.

Gas Mixture Ratios of O_2 and N_2	Maximum Electric Field, Emax (10^7 V/m)				
	0.5 cm	**1.0 cm**	**1.5 cm**	**2.0 cm**	**2.5 cm**
30% + 70%	2.26E+07	2.07E+07	2.20E+07	2.23E+07	2.47E+07
50% + 50%	2.63E+07	2.55E+07	2.41E+07	2.60E+07	2.60E+07
70% + 30%	2.95E+07	2.89E+07	2.68E+07	2.57E+07	2.84E+07

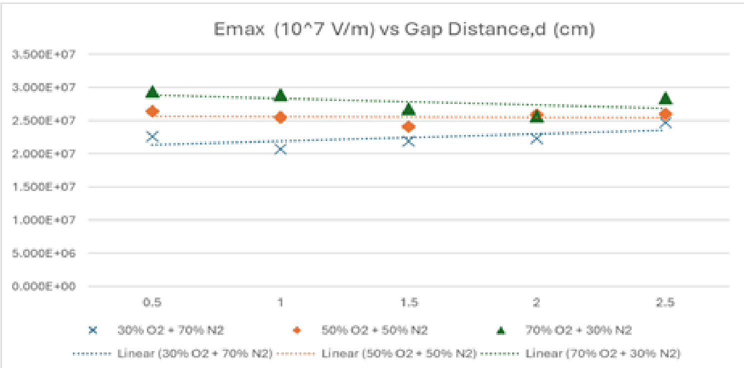


Figure 1.8: Maximum electric field, E_{max} (V/m) against gap distance (cm) for each type of gas mixtures ratios.

1.4.3 FIELD UTILIZATION FACTOR AGAINST GAP DISTANCE

Field utilization factor was almost equivalent in all mixtures of O_2 and N_2 at greater distances between the plates. As per Table 1.4 and Figure 1.9, the values of 1.5 cm, 2.0 cm and 2.5 cm were 0.1563, 0.1265 and 0.1066 respectively. This implies that there is less influence of gas composition on η, the greater the gap. The electric field near needle electrode is very inhomogeneous at small gaps like 0.5 cm, and the gas composition plays a correspondingly more significant role. Conversely, greater gaps produce a more homogenous field whereby, the value of η is more influenced by the shape and distance of the electrodes than the type of gases.

Table 1.4: Field utilization factor values for each gas mixture ratio.

Gas Mixture Ratios of O_2 and N_2	Field Utilization Factor, η				
	0.5 cm	**1.0 cm**	**1.5 cm**	**2.0 cm**	**2.5 cm**
30% + 70%	0.2806	0.1951	0.1563	0.1265	0.1066
50% + 50%	0.2806	0.1952	0.1563	0.1265	0.1066
70% + 30%	0.2806	0.1952	0.1563	0.1265	0.1066

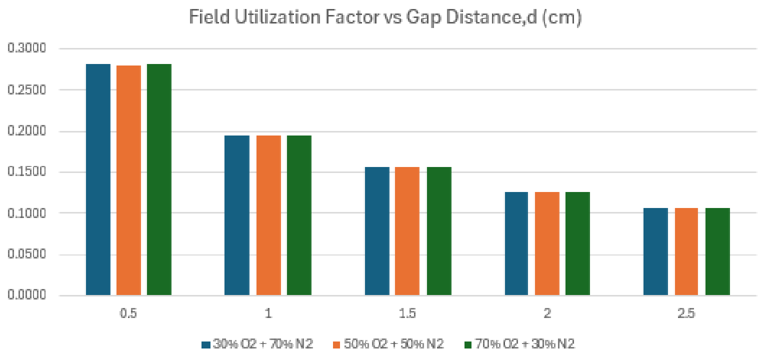


Figure 1.9: Field utilization factor against gap distance (cm) for each type of gas mixtures ratios.

1.5 CONCLUSION

The main point that can be made is that an increase in the amount of nitrogen in the gas mixture leads to an increase in dielectric strength and therefore has greater breakdown voltage. This is what makes nitrogen a potential constituent of alternative insulating gases [3]. Experimental findings also show that breakdown voltage is increasing with gap distance not in a linear manner since there are influences of non-uniform electric fields at the needle electrode. This was further reinforced with simulations conducted using the FEMM software which demonstrates how field intensity is concentrated at the needle tip and that it depends on the length of the gap which influences the onset of breakdown. All these results agree with previous high-voltage insulation systems under which FEMM proved to be accurate in electric fields [4]. Since industries currently plan to eliminate the use of SF_6 in the light of its high global warming potential, the findings of this research can help to come up with greener insulation materials. The cost effective, non-toxic and non-flammable mixtures of O_2 and N_2 investigated in this paper provide a satisfactory solution that has a good insulation property. This study provides a useful baseline upon which other future research can be based although additional studies are still required particularly at greater pressures and in alternative arrangements.

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