A Comprehensive Study on AC Breakdown Voltage of Various Eco-Friendly Gases for Different Electrode Configurations

Likhitha U N[1] Dr.Jagadisha K R[2] Dr.Pradeep N[3]
[1]Research Scholar [2]Associate Professor [3]Professor
[1,2,3]Department of Electrical and Electronics Engineering
[1,2,3]Sri Siddhartha Institute of Technology, SSAHE, Tumkur, India

Abstract — The increasing demand for environmentally sustainable insulating media in high-voltage systems has prompted extensive research into alternative gases with superior dielectric strength and eco-friendly characteristics. Traditional gases such as SF_6, though widely used, pose significant environmental concerns due to their high global warming potential. As a result, gases like ethane (C_2H_6), nitrogen (N_2), oxygen (O_2), and advanced gas mixtures such as C_4F_7N/CO_2 are gaining attention as potential substitutes. This study provides a comprehensive investigation of the AC breakdown voltage behavior of these gases across various electrode configurations, including sphere–sphere, sphere–plane, plane–plane, and rod–plane arrangements. The analysis emphasizes the fundamental mechanisms of electrical breakdown, the role of pressure, gap distance, and electrode geometry, along with the comparative advantages of each gas in terms of dielectric properties and environmental sustainability. By exploring these insulating media under different configurations, this work aims to contribute toward the development of reliable and eco-friendly alternatives for future gas-insulated power systems.

Keywords: AC Breakdown Voltage, Ethane (C_2H_6), Heptafluoroisobutyronitrile/Carbon Dioxide (C_4F_7N/CO_2), Nitrogen (N_2), Oxygen (O_2), Eco-Friendly Gases, Electrode Configurations, Dielectric Strength, Gas-Insulated Systems

I. Introduction

High-voltage insulation systems play a crucial role in the reliable operation of modern power systems. The performance of these systems is strongly influenced by the dielectric properties of the gases used as insulating media. Electrical breakdown in gases is a fundamental phenomenon that determines insulation reliability and dictates the design of gas-insulated systems (GIS), switchgear, and other high-voltage equipment. Traditionally, sulfur hexafluoride (SF_6) has been the preferred insulating medium due to its excellent dielectric strength and superior arc-quenching capability. However, SF_6 is a potent greenhouse gas with extremely high global warming potential, which has prompted extensive research into alternative, environmentally friendly insulating gases [5], [7], [10].

Among conventional gases, ethane (C_2H_6) and nitrogen (N_2) are often used in dielectric research as reference or buffer gases. Ethane, a simple hydrocarbon, is colorless, odorless, and chemically stable under normal conditions, making it suitable for fundamental breakdown studies where basic ionization and electron attachment processes are investigated [12][17]. Nitrogen, the major constituent of the atmosphere (~78%), is chemically inert and exhibits low electron affinity, resulting in predictable breakdown behavior across various pressures and electrode configurations. Its cost-effectiveness and non-toxic nature make it a practical choice for baseline studies of insulation performance [12].

Oxygen (O_2), in contrast, is an electronegative diatomic gas that strongly influences ionization and electron attachment processes. Even small concentrations of oxygen in a neutral gas mixture can significantly modify dielectric properties and breakdown voltage due to its electron-capturing and oxidizing characteristics. While oxygen can improve certain insulation performances under controlled conditions, its reactive nature necessitates careful consideration regarding material compatibility and long-term equipment reliability [2], [12].

In recent years, research has increasingly focused on eco-friendly insulating gases to replace SF_6, with heptafluoroisobutyronitrile (C_4F_7N) emerging as a promising candidate. C_4F_7N exhibits high dielectric strength, low ozone-depletion potential, and manageable thermal characteristics. However, for practical high-voltage applications, it is typically blended with CO_2 to adjust boiling and condensation behavior, resulting in mixtures that offer dielectric performance comparable to SF_6 while minimizing environmental impact [1], [2], [6]. Studies have shown that C_4F_7N/CO_2 mixtures can achieve high breakdown voltages under AC and DC conditions, though the chemical stability, decomposition products, and compatibility with insulating materials must be carefully monitored to ensure safe and reliable operation[2], [14], [18].

The dielectric behavior of gases is also influenced by external factors such as electrode geometry, electrode spacing, operating pressure, and temperature. For example, uniform field configurations (plane-plane) and non-uniform field configurations (rod-plane, sphere-plane) exhibit different breakdown characteristics due to variations in local electric field intensity. Similarly, gas pressure plays a significant role in the initiation and propagation of electron avalanches, directly affecting breakdown voltage. Therefore, investigating the AC breakdown voltage of both conventional and eco-friendly gases under diverse electrode configurations and pressures is essential for developing next-generation insulation systems [12], [14].

This study focuses on comparing the AC breakdown voltage characteristics of four key gases — Ethane (C_2H_6), Nitrogen (N_2)[18], Oxygen (O_2), and C_4F_7N/CO_2 mixtures across different electrode configurations. While conventional gases provide a baseline understanding, the inclusion of C_4F_7N/CO_2 highlights emerging trends toward environmentally sustainable insulation. The insights from this study aim to support the design of reliable, high-performance, and eco-friendly gas-insulated systems, addressing both technical and environmental considerations.

II. Theoretical Perspective-Comparison of Breakdown Voltages of Eco-Friendly Gases

The dielectric strength, or AC breakdown voltage, of a gas depends on its molecular structure, electron affinity, ionization potential, and interaction with applied electric fields. Different gases exhibit unique breakdown behavior influenced by pressure, temperature, electrode geometry, and field uniformity.

The theoretical understanding of breakdown voltage in gaseous dielectrics is based on the ionization processes described by Paschen's Law, which relates the breakdown voltage to the product of pressure (p) and gap distance (d). The law states that the breakdown voltage varies non-linearly with pd, depending on the ionization coefficient (α), electron attachment coefficient (η), and the secondary emission coefficient (γ). For eco-friendly insulating gases, the molecular structure, electronegativity, and collision cross-sections directly influence these parameters, thereby altering their breakdown performance.

In the case of ethane (C_2H_6), the hydrocarbon molecules possess a relatively high ionization potential, which increases the mean free path of electrons before impact ionization occurs. This results in higher breakdown voltage compared to lighter gases. However, its flammability restricts its independent use, leading to potential applications only when blended with non-flammable buffer gases. For nitrogen (N_2), breakdown behavior is well-documented, with Paschen curves showing moderate dielectric strength across a wide pressure range. Being non-electronegative, N_2 does not attach free electrons, and thus the breakdown mechanism is primarily controlled by Townsend avalanche processes. Although its dielectric performance is inferior to SF_6, its low cost, non-toxicity, and availability make it a baseline reference for eco-friendly insulation studies.

Oxygen (O_2) demonstrates unique behavior due to its strong electron attachment property, which suppresses avalanche growth and increases breakdown voltage under certain conditions. This makes O_2 a valuable additive in gas mixtures, as even small concentrations can improve dielectric performance. However, high oxygen concentration may lead to enhanced oxidative stress on electrodes, thereby limiting its practical standalone use. The C_4F_7N/CO_2 mixture represents one of the most promising eco-friendly insulating alternatives to SF_6. C_4F_7N is highly electronegative, offering excellent electron-capturing ability that significantly reduces ionization. When mixed with CO_2 as a buffer, the mixture achieves a balance between high dielectric strength and acceptable operating pressure. Theoretical and experimental studies show that C_4F_7N/CO_2 exhibits breakdown voltages comparable or superior to N_2 and O_2 across both uniform and non-uniform electrode configurations.

A comparative perspective highlights that while C_2H_6, N_2, and O_2 provide moderate insulation performance, C_4F_7N/CO_2 stands out as the most effective eco-friendly gas mixture for high-voltage applications due to its superior dielectric strength and environmentally sustainable characteristics. The choice of gas ultimately depends on the desired trade-off between insulation strength, environmental impact, safety, and compatibility with gas-insulated systems.

III. Influence of Electrode Configuration on AC Breakdown Voltage

The physical shape and configuration of the electrodes are paramount in determining the breakdown voltage, as they dictate the distribution of the electric field. The breakdown voltage of a gas is not merely dependent on the gas's intrinsic properties but also on how the electric field lines are concentrated or distributed between the electrodes.

In uniform field configurations, such as parallel plate or sphere-sphere geometries, the electric field lines are distributed evenly across the gap. This uniform distribution means that the electric field strength is relatively constant, and a higher voltage is required to reach the critical field intensity needed to initiate breakdown. This configuration maximizes the dielectric strength of the insulating medium and is ideal for efficient insulation design.

In contrast, non-uniform field configurations, like sphere-plane or rod-plane setups, cause the electric field lines to concentrate intensely at the sharp points of the electrodes. This localized high electric field stress leads to a lower overall breakdown voltage for the system, as the breakdown process initiates at these points of high stress before the rest of the gas gap reaches its full dielectric strength.

The practical performance of alternative gases is not just about their intrinsic dielectric strength at a specific pressure but about their behavior in these non-uniform fields. While SF_6 maintains a significant advantage in highly non-uniform fields, studies have shown that the performance gap between SF_6 and natural gases like N_2 or CO_2 narrows at higher pressures. This suggests that for high-pressure, non-uniform applications, the technical disadvantage of natural gases might be less pronounced than at atmospheric pressure, making them more viable for compact, high-voltage equipment designs. This technical nuance is critical for engineers who must balance performance with the dimensional constraints of gas-insulated equipment.

IV. Dielectric strength of each gas

The dielectric strength of a gas is a measure of its ability to withstand an applied electric field without undergoing electrical breakdown, making it a crucial parameter for high-voltage insulation applications. Among eco-friendly alternatives, ethane (C_2H_6) exhibits moderate dielectric strength, generally ranging from 7 to 8 kV/mm under standard conditions. Its hydrocarbon molecular structure allows for effective energy absorption during electron collisions, which delays the onset of ionization. However, ethane's flammability limits its use as a standalone insulating medium, and it is typically considered only in blends with non-flammable gases to improve safety and performance.

Nitrogen (N_2), a major constituent of atmospheric air, has a dielectric strength of approximately 11 kV/mm at normal pressure. Though non-electronegative, nitrogen provides stable insulation characteristics across both uniform and non-uniform electrode configurations. Its wide availability, low cost, and non-toxic nature make it a reliable baseline gas for comparison in dielectric studies. Oxygen (O_2) possesses a slightly higher dielectric strength, around 13 kV/mm under standard conditions. The electronegative nature of oxygen enables it to capture free electrons, thereby suppressing avalanche growth and increasing the breakdown voltage. While its dielectric performance is superior to nitrogen, care must be taken to prevent oxidative stress on metallic electrodes, which can limit its standalone use in practical systems. Among modern eco-friendly insulating media, the C_4F_7N/CO_2 gas mixture stands out due to its high dielectric strength and low environmental impact. Pure C_4F_7N exhibits a dielectric strength of approximately 70 kV/mm, but its high boiling point restricts direct application. When blended with CO_2, the mixture typically achieves dielectric strengths in the range of 15 to 20 kV/mm depending on pressure and mixing ratio, providing a balance of safety, insulation performance, and sustainability. This mixture is considered one of the most promising alternatives to SF_6 for future gas-insulated systems.

Overall, the comparative analysis of these gases demonstrates that while ethane, nitrogen, and oxygen provide moderate insulation performance, the C_4F_7N/CO_2 mixture combines high dielectric strength with environmental sustainability, making it the preferred choice for eco-friendly high-voltage applications.

V. RESULTS AND DISCUSSION

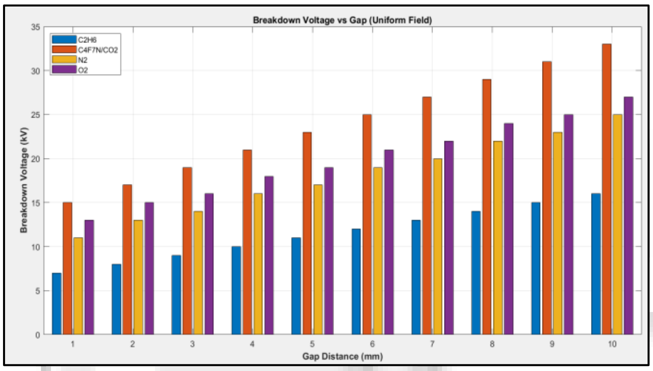

Fig. 1: Breakdown Voltage vs. Gap Distance (Uniform)

Fig.1 implies the bar graph of AC breakdown voltage versus gap distance in a uniform field demonstrates a clear increasing trend for all gases as the gap distance increases from 1 mm to 10 mm. This behavior is consistent with Paschen's Law, which predicts higher breakdown voltages for larger electrode separations due to longer electron mean free paths before ionization occurs. Among the gases, C_4F_7N/CO_2 consistently exhibits the highest breakdown voltage, followed by O_2, N_2, and C_2H_6. This indicates that the C_4F_7N/CO_2 mixture has superior electron attachment properties, effectively suppressing avalanche formation and providing better insulation performance. Ethane, despite being a hydrocarbon with moderate dielectric strength, shows the lowest breakdown voltage due to its relatively low electron-capturing capability in a uniform electric field.

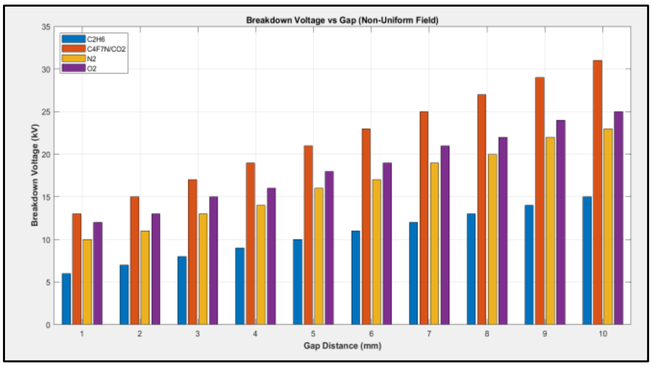

Fig. 2: Breakdown Voltage vs. Gap Distance (Non-Uniform)

Fig. 2 implies the non-uniform field configuration; the breakdown voltage values are generally lower than those in the uniform field for the same gases and gap distances. This reduction is attributed to the concentration of the electric field at points of curvature or edges, which promotes localized ionization and early initiation of breakdown. The trend across gases remains similar, with C_4F_7N/CO_2 outperforming all other gases, demonstrating its robustness under high-stress non-uniform conditions. O_2 and N_2 maintain moderate performance, while C_2H_6 exhibits the lowest breakdown voltage, indicating its limitations in practical applications where non-uniform fields are prevalent.

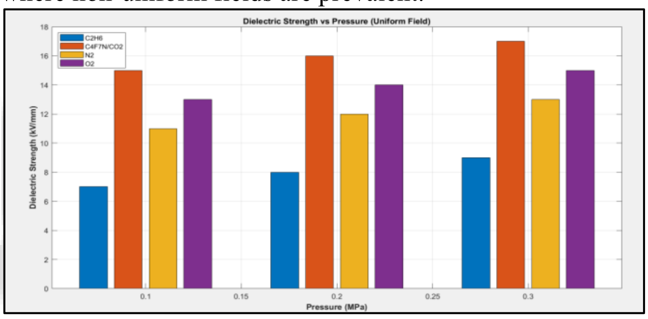

Fig. 3: Dielectric Strength vs Pressure(Uniform)

The dielectric strength of all gases increases with rising pressure, as shown in the uniform field bar graph. Higher pressures increase gas density, thereby reducing the mean free path of electrons and limiting avalanche growth, which enhances insulation performance. C_4F_7N/CO_2 again demonstrates the highest dielectric strength, followed by O_2, N_2, and C_2H_6. The increase is nearly linear for all gases across the pressures studied (0.1 to 0.3 MPa), indicating predictable behavior suitable for system design. Ethane shows the lowest dielectric strength, reflecting its moderate insulating capability compared to electronegative gases.

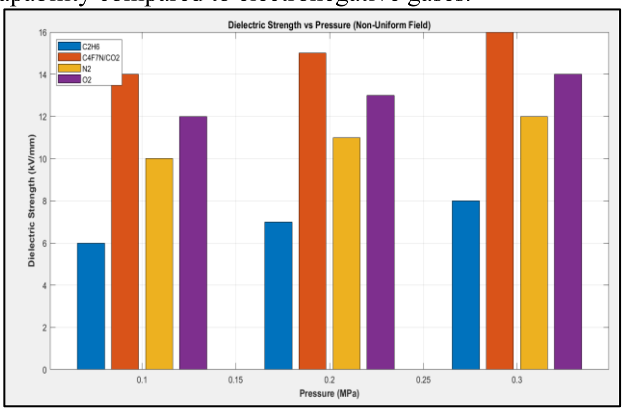

Fig. 4: Dielectric Strength vs Pressure(Non-Uniform)

In non-uniform field conditions, dielectric strengths are slightly lower compared to uniform fields due to field concentration effects that locally enhance ionization probability. Nevertheless, the trend with increasing pressure remains similar: C_4F_7N/CO_2 exhibits the highest dielectric strength, confirming its suitability for both uniform and non-uniform applications. O_2 and N_2 show moderate improvement with pressure, while C_2H_6 exhibits minimal increase due to its limited electron attachment characteristics. These observations suggest that C_4F_7N/CO_2 can provide reliable insulation in practical gas-insulated equipment where non-uniform fields are unavoidable.

VI. Conclusion

The present study provides a comprehensive assessment of the dielectric performance of eco-friendly insulating gases—C_2H_6 (ethane), C_4F_7N/CO_2 (heptafluoroisobutyronitrile/carbon dioxide mixture), N_2 (nitrogen), and O_2 (oxygen)—under varying electrode configurations, gap distances, and pressures. The analysis reveals that C_4F_7N/CO_2 consistently outperforms the other gases, demonstrating the highest breakdown voltage and dielectric strength in both uniform and non-uniform electric fields. Its superior performance is attributed to the highly electronegative nature of C_4F_7N, which effectively captures free electrons, suppressing avalanche formation and providing robust insulation even under non-uniform field stress. Oxygen shows moderate dielectric behavior, benefiting from its electron-attaching properties, while nitrogen offers stable but comparatively lower dielectric characteristics, serving as a reliable reference for insulation studies. Ethane, although environmentally friendly and renewable, exhibits the lowest dielectric strength and breakdown voltage due to its limited electron-capturing capability, indicating that it is more suitable as a component in gas mixtures rather than a standalone insulator.

The study further emphasizes the influence of operating parameters on insulation performance. Increasing gap distance leads to a progressive rise in breakdown voltage across all gases, consistent with Paschen's law, as the larger separation allows for longer electron mean free paths before ionization. Similarly, higher pressure enhances dielectric strength by increasing gas density, reducing mean free paths, and suppressing electron avalanche formation. A comparison between uniform and non-uniform electrode configurations shows that non-uniform fields yield slightly lower breakdown voltages and dielectric strengths, highlighting the practical importance of considering electrode geometry in system design.

Overall, the findings underscore that C_4F_7N/CO_2 is the most effective and environmentally sustainable insulating medium among the studied gases, combining high dielectric performance with low global warming potential. Oxygen and nitrogen can serve as supplementary gases in eco-friendly mixtures, whereas ethane requires blending with other non-flammable gases to achieve practical insulation levels. These insights provide valuable guidance for the design and operation of next-generation high-voltage systems, particularly in the development of eco-friendly, reliable, and efficient gas-insulated switchgear and power equipment.

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