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Studies on Different Dielectric Properties of Different Insulating Gases and Gas Mixtures as an Alternative to SF_6 -Review

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ABSTRACT

SF_6 gas is considered as one of the most noxious kinds of atmospheric greenhouse gases with global warming potential (GWP) 23,500[10] times higher than that of CO_2 and shelf life of 3200 years in the atmosphere. With threat of global climate change, policy makers all over the world have made regulations which promote renewable energy technologies. Developing countries including India are increasingly emphasising the need to rapidly restructuring of their energy system. A replacement for SF_6 has been in testing and development for over a decade and have come up with different combination of gas and gas mixtures like N_2, CO_2, CF_3I (Trifluoroiodo-methane), C_4-fluoronitrile and C_5-Fluoroketones along with different combination of the later with SF_6. In recent years many gases are being investigated for breakdown voltage and partial discharge characteristics, such as $C_5F_{10}O$ (C5 per uorinatedketone), $C_5F_{10}O/N_2$ mixture, SF_6 and CO_2 gas mixture, Pd_3-TiO_2(101) (Titanium dioxide), C_4F_7N/CO_2 mixed gases (Fluro nitrile and carbon dioxide), HFO-butene/ CO_2 gas mixture (Hydrofluroolefin).

In the present paper an attempt is made to compare different potential alternatives for SF_6 along with their dielectric properties.

Keywords: CF_3I (Trifluoroiodo-methane), C_4-fluoronitrile and C_5-Fluoroketones, $C_5F_{10}O$ (C5 per uorinatedketone), C_4F_7N/CO_2 mixed gases (Fluro nitrile and carbon dioxide), HFO-butene/ CO_2 gas mixture (Hydrofluroolefin).

INTRODUCTION

The environmentalist and power engineers have sternly considered the benefaction of SF_6 gas to depletion of ozone and the global greenhouse effect. In spite of its good electrical insulation properties, questions regarding use of SF_6 gas. When this gas is subjected to electrical discharges, is believed to form highly toxic and corrosive compounds. SF_6 and its disintegration products generate CuF_2, AIF_3 and other noxious substances, when they react with copper, aluminium and other materials of metallic composition, there by affecting the properties of metallic materials. Due to corona discharge and spark discharge, SF_6 emitting SF_4 gas. This SF_4 gas reacts with O_2 to form SOF, SOF_2, SO_2F_2 other harmful substances in electrical apparatus.

SF_6 is an electronegative gas and it has dielectric strength three times that of air, the outstanding properties of SF_6 have resulted in its extensive use as an insulating gas in high voltage equipment. On the other hand, it is a highly potent greenhouse gas due to its high global warming potential,. Alternative insulating gases to replace SF_6 have been investigated in recent decades. As the insulating gas of Gas Insulated Switchgear (GIS), SF_6/N_2 gas mixture can not only reduce the consumption of SF6 in power system, but also effectively alleviate SF6 greenhouse effect and solve the problem of high liquefaction temperature[10].

The research, so far, into alternative gases has shown that CF_3I and its gas mixtures have promising dielectric properties comparable to those of SF_6. It was found that, for various gap geometries (rod plane and plane-plane electrodes) and lengths, CF_3I mixtures exhibit promising breakdown characteristics comparable to those of SF6 gas based on the measured 50% breakdown voltage (U50). These encouraging results led to a trial of CF_3I as the insulation gas on practical 11 kV low-current switches and circuit breakers[2].

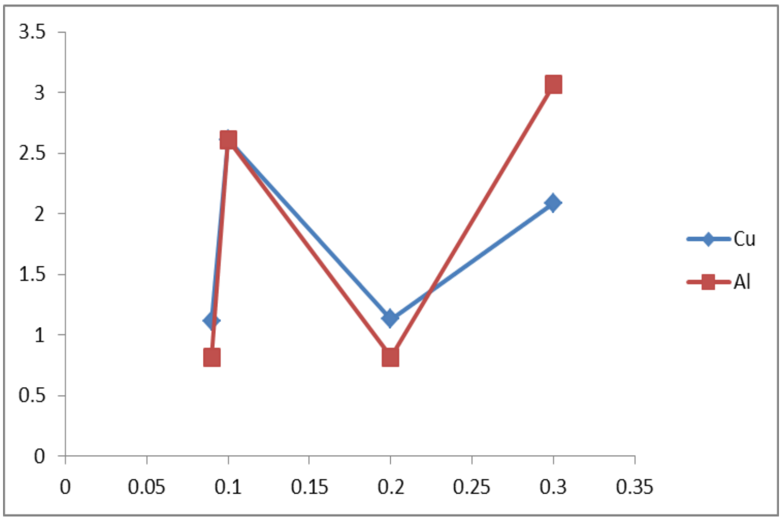
(HFO-butene) is regarded as a promising eco-friendly insulating gas to replace the sulfur hexafluoride (SF_6) used in medium-voltage gas insulated equipment (MV-GIE)[8].

The Pd_3-TiO_2(101) surface exhibits high gas sensitivity and selectivity to SOF2 and SO2F2 molecules due to decrease in the conductivity of the material. The most stable configuration for Pd cluster on TiO_2 (101) surface is triangular structure[5].

Comparison of Different Insulating Gases

Comparison of SF_6/N_2 mixture[3]

SF_6/N_2 gas mixture can not only reduce the consumption of SF_6 in power system, but also effectively alleviate SF6 greenhouse effect. Since SF_6/N_2 can decompose under the alternating current partial discharge (PD), its decomposition characteristics are closely related to PD attributes. Therefore, the fault diagnosis method can be established through its PD decomposition characteristics. SF_6/N_2 gas mixture under PD can decompose to SOF2, SO2, SO2F2, SOF4 CF4, CO2, NO, NO2 and NF3. The gas production laws of these decomposed components are quite different under different PD intensity. The content of NO_2 and (SO2F2 SOF2 SOF4 SO2) increases linearly with discharge quantity, which can be used as the characteristic quantity to judge the whole process of PD. In short-term discharge, the content of SO_2F_2 increases greatly with time, which can be used as the characteristic quantity to judge the early PD. conventional GIS, GIS using SF6/N2 gas mixture will inevitably be damaged during manufacturing, transportation, installation and operation, resulting in some internal insulation defects. These insulation defects will deteriorate gradually in the long-term operation of GIS, and when they reach a certain degree, they will induce partial discharge (PD) in the equipment.

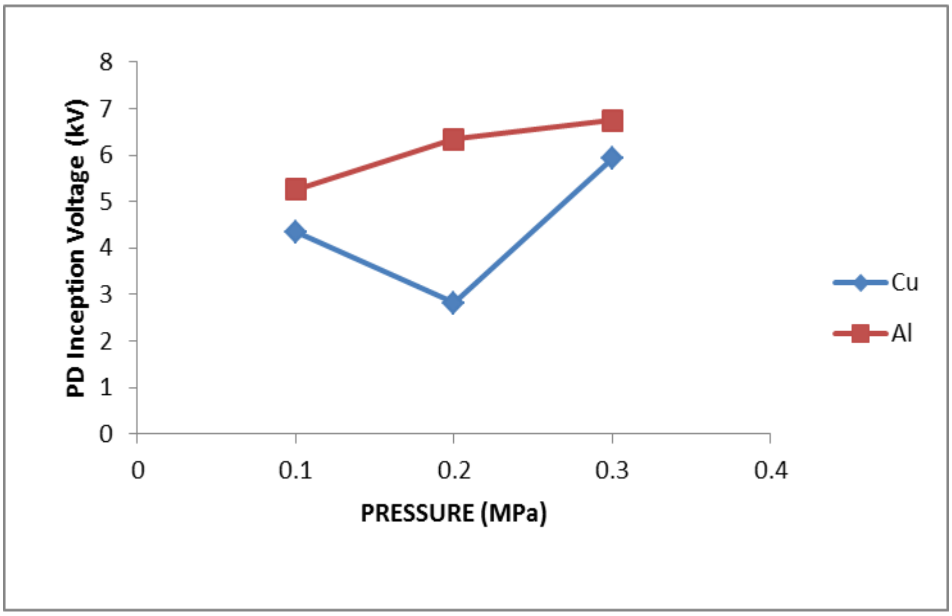


Comparison of conducting particles in N_2:SF_6

From the above graphs it can be seen that copper particle at 10 mm gap distance has a higher inception voltage in N_2:SF_6 gas mixtures up to 0.2MPa. Higher the PD inception voltage, better is the performance of the insulating media.

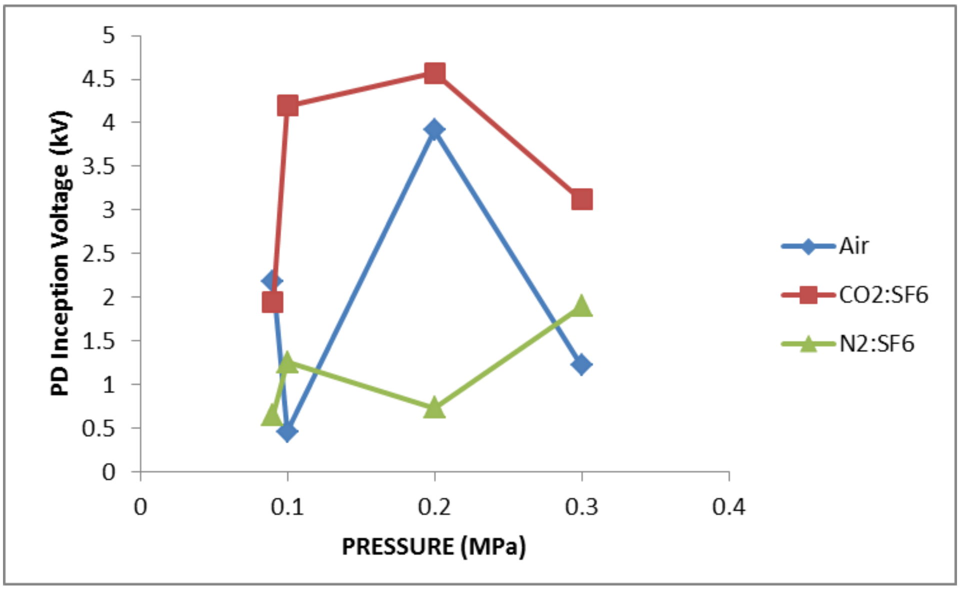
Comparison of SF6/CO_2 mixture[10]

Though CO_2 is no match for SF_6, the later is being investigated with other elements, as an alternative with other gas mixtures because of high global warming potential of SF_6 gas. The particle contamination in CO_2 are the major cause for the partial discharges which in turn cause the insulation failure. The particle contamination inside the GIS may occur because of the manufacturing process, from mechanical vibrations, moving parts of the system such as breakers. It can also be from the negligence during the maintenance inside the GIS or from corrosion or decomposition of the metallic products. The study of PD characteristics for different gas pressure and different particle contaminants can give a real picture of the dielectric strength of insulating medium used in GIS as an alternative for SF_6. The study of PD characteristics for air at different pressures and particles can be taken as reference and compared with other gases like CO_2 and its mixtures.



Comparison of conducting particles in $CO_2:SF_6$

From the above graphs it can be seen that copper particle at 10 mm gap distance has a lower PD inception voltage in air and $CO_2:SF_6$. Higher the PD inception voltage, better is the performance of the insulating media.



Behaviour of 3 gases

The Fig.2.2.2 shows the behaviour of the three gas insulating media in the presence of Aluminium particles at different pressures at 10 mm gap spacing. The CO_2: SF_6 gas mixture has the better performance with respect to PD inception voltage even bettering N_2: SF_6 gas mixture of the same proportion.

Comparison of SF_6 and CF_3I mixture[2]

CF_3I mixture and its potential to replace SF_6in high voltage equipment. 50% breakdown tests conducted on three electrode configurations (rod-plane, plane-plane and coaxial) were used to characterise 30:70% mixture of CF_3I -CO_2. The breakdown strength of the mixture for coaxial electrode was more than two times higher than air. In comparison, breakdown strength of pure SF_6 is about three times higher than air. The insulation capability makes CF_3I a feasible alternative to SF_6 in a GIL system where arc quenching is not required.

Partial pressure of CF_3I in the mixture is selected by a trade-off between three basic factors; boiling point of the gas mixture, insulation strength, and the by-products of the gas mixture upon each electrical discharge.

Saturation Vapour Pressure

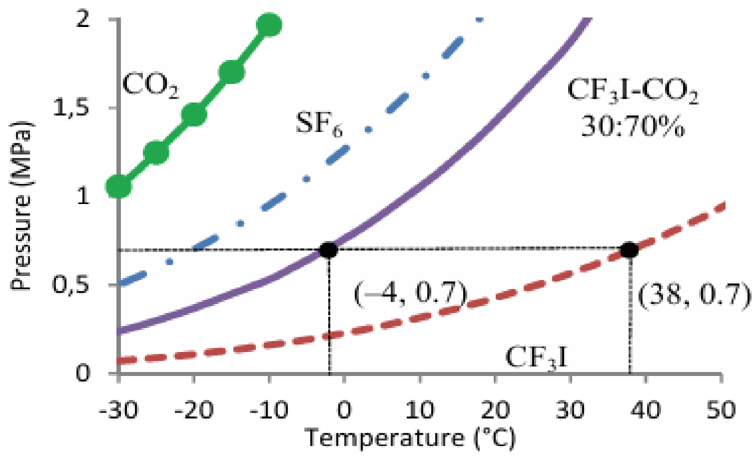


Figure 2.3.1.1 : Saturation vapour pressure curve of SF6, CF3I, CO2 and 30:70% CF3I-CO2 mixture.

Typically, in a GIL system, SF6 gas is pressurised at 0.7 MPa. It can be seen from Figure 2.3.1.1 that the boiling point of CF_3I at 0.7 MPa is 38°C, an indication that a buffer gas such as carbon dioxide (CO_2) needs to be added to CF_3I in order to reduce the boiling temperature.

Ionisation Coefficients

Effective ionisation coefficients of different gases and gas mixtures were computed using Bolsig+ software which applies the two-term approximation of Boltzmann equation [4]. Figure 2 shows the 1 2 pressure-reduced ionisation coefficient $(\alpha - \eta) / p$ as a function of E / p for different pure gases and CF_3I mixtures. It can be seen from Figure 2 that the critical reduced field strength at which $(\alpha - \eta) = 0$ for CF_3I is 108 kV/cm bar compared to 89 kV/cm bar in SF6 [5]. which indicate that pure CF_3I has a dielectric strength of around 1.2 times higher than that SF6.

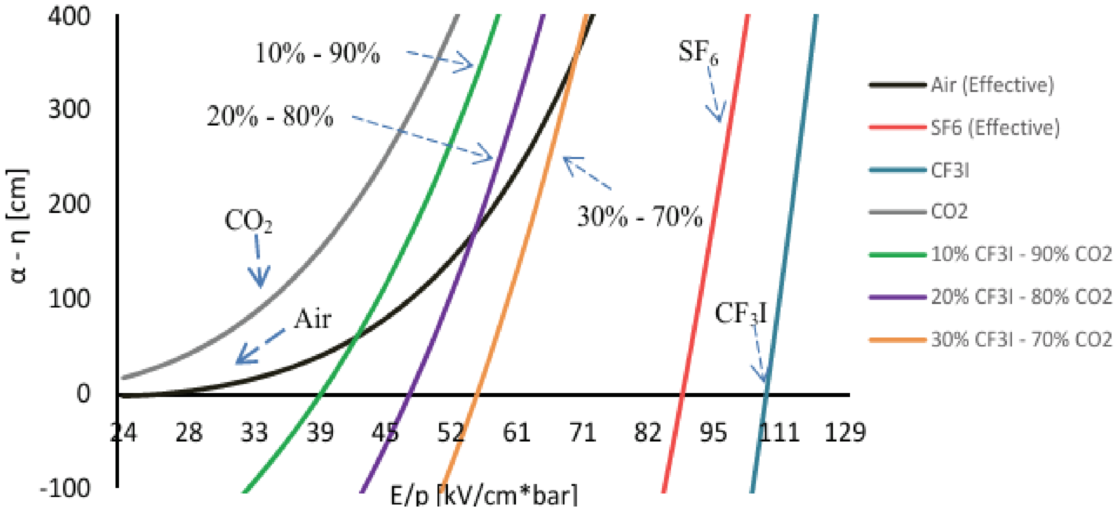
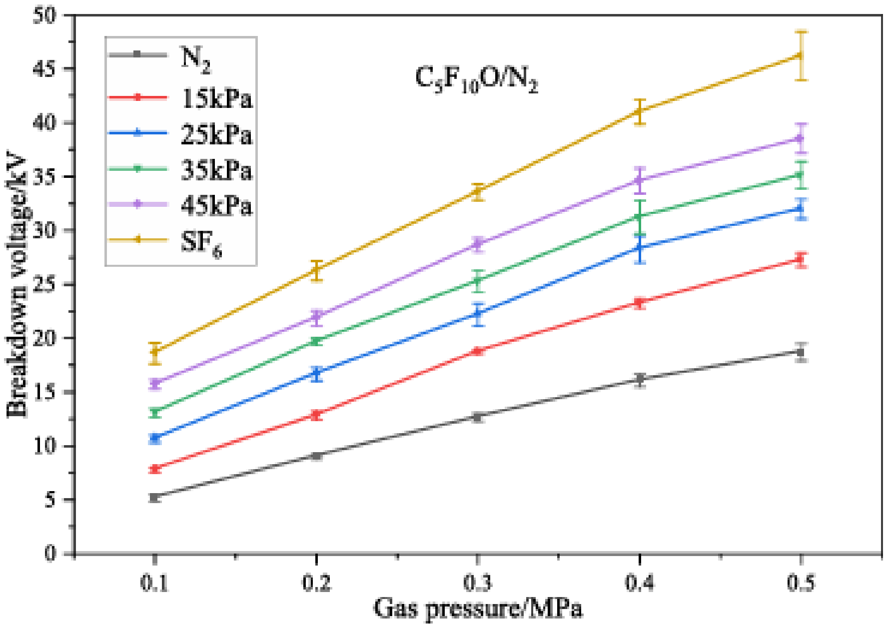


Figure 2.3.2.1: Effective ionisation coefficients in pure gases (Air, SF6, CF3I and CO2) and CF3I-CO2 mixtures (10%-90%, 20%-80% and 30:70%)

Figure 2.3.2.1 shows that 30:70% mixture ratio has a higher reduced field strength E/p compared to CF_3I CO_2 mixtures with low CF_3I contents. The 30:70% mixture ratio is considered to be most appropriate for gas-insulated switchgear (GIS) applications. the interruption capability of CF_3I -CO_2 mixtures is far superior to that of CF3I-N2 mixtures. With only 30% of CF_3I in the CF_3I -CO_2 mixture, the insulation performance was reported to be approximately 0.75 to 0.80 times that of SF6. The 30:70% mixture ratio, therefore, offers a reasonably high dielectric strength while been able to sustain its gaseous form at 0.7 MPa with a boiling temperature of mixture of around –4°C. Furthermore, by-products produced during arcing such as iodine can be reduced substantially using 30:70% mixture, It is important to minimise iodine deposition as it can compromise CF_3I insulation performance.

Comparison of $C_5F_{10}O/N_2$ mixture[1]

It is found that the AC breakdown voltage of the $C_5F_{10}O$ gas mixtures increases gradually with both the gas pressure and the content of $C_5F_{10}O$. As the partial pressure of $C_5F_{10}O$ increases, the relative insulation strength increasing trend of the $C_5F_{10}O$ gas mixtures becomes less obvious with the increase in the gas pressure. The AC breakdown voltage of $C_5F_{10}O$ /Air gas mixture is higher than that of $C_5F_{10}O$ /N2 gas mixture under the same conditions. The breakdown voltage of $C_5F_{10}O$ /Air gas mixture is less affected by gas pressure. When the partial voltage of $C_5F_{10}O$ is greater than 15kPa, the breakdown voltage of $C_5F_{10}O$ /Air gas mixture increases with the partial voltage of $C_5F_{10}O$ at a rate similar to that of $C_5F_{10}O$ /N2 gas mixture.



F, Figure 2.4.1: Relation between breakdown voltage and gas pressure of $C_5F_{10}O$ /N_2 gas mixture.

Figure shows the Relation between breakdown voltage and gas pressure of $C_5F_{10}O$ /N_2 gas mixture. When the gas pressure is in the range of 0.1-0.4MPa, the breakdown voltage of each gas mixture increases linearly with the gas pressure. While the increase rate of the AC breakdown voltage of $C_5F_{10}O$ gas mixtures and SF6 are reduced, showing a certain saturation trend at gas pressures higher than 0.4MPa.

Comparison of C_4F_7N /CO_2 mixture[6]

Research indicates that adding an appropriate amount of O_2 to a C_4F_7N /CO_2 mixture to form a ternary gas mixture helps suppresdeep decomposition and the formation of solid byproducts. Therefore, a thorough investigation into the electrical performance of such mixtures is essential the application of the C_4F_7N /CO_2/O_2 ternary mixture warrants further attention to the specific properties of the gas-solid interface. Additionally, due to the relatively lower stability of C_4F_7N compared to SF_6, ionization and decomposition may occur under discharge or overheating conditions.

The addition of O_2 can enhance the insulation performance and chemical stability of C_4F_7N/CO_2 mixed gases during partial discharge to a certain extent. However, the influence of O2 on the surface flashover characteristics at gas-solid interfaces, as well as the compatibility and interaction mechanisms between gaseous and solid materials, remain poorly understood. The surface flashover characteristics of epoxy resin in C_4F_7N/CO_2 /O_2 ternary mixed gases, exploring the differences in solid surface ablation characteristics under various conditions of gas pressure, C_4F_7N mixture ratio, and O2 concentration. The peak current of the flashover discharge channel increases significantly with higher C_4F_7N concentration and gas pressure, while the peak current remains relatively stable across different O_2 concentrations.

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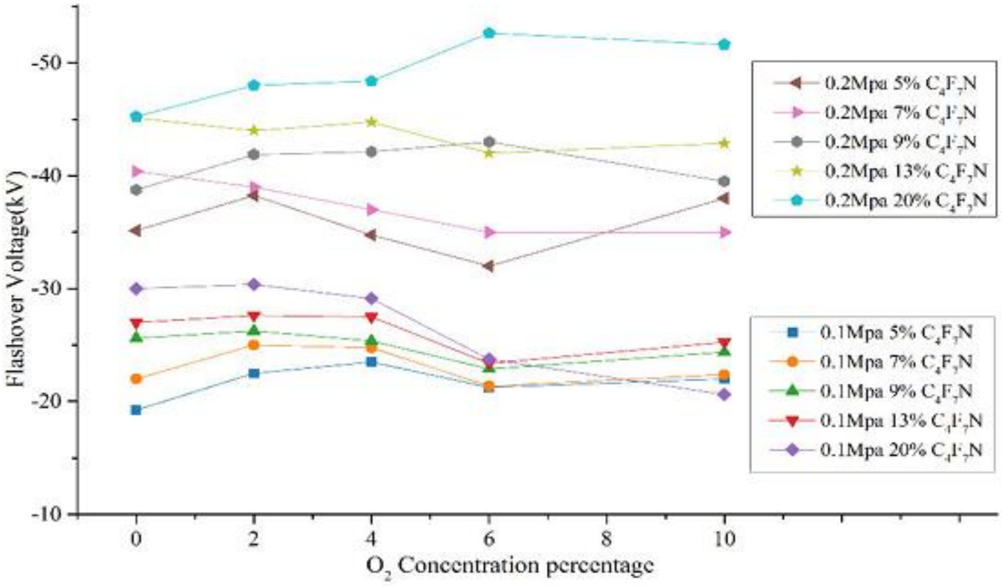

Fig 2.5.1: Variation of flashover voltage of mixed gas with O2 concentration.

Figure 2.5.1 illustrates the variation in flashover voltage with oxygen con centration in C_4F_7N/CO_2 /O_2 ternary mixtures at pressures of 0.1 MPa and 0.2 MPa, under a slightly non-uniform electric field. At a pressure of 0.1 MPa, the oxygen concentration significantly affects the flashover voltage of the gas mixture. As the oxygen content increases, the flashover voltage generally decreases. When the C_4F_7N concentration is 20%, the reduction in flashover voltage is most pronounced with increasing oxygen content.

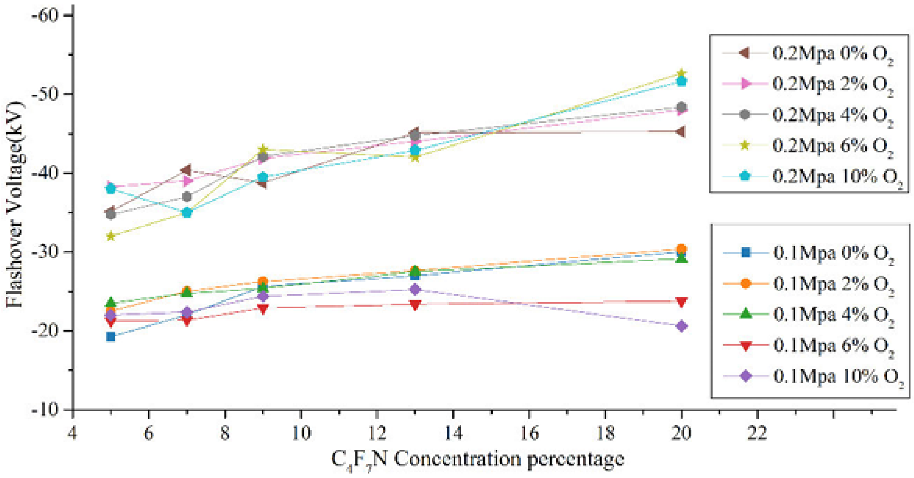

Fig: 2.5.2 Variation of flashover voltage of mixed gas with C_4F_7N concentration.

Figure 2.5.2 illustrates the variation in flashover voltage with C_4F_7N concentration under different oxygen contents. It is evident that the flashover voltage of the ternary gas mixture increases overall with the rise in C_4F_7N concentration. At lower pressures, the increase in flashover voltage with C_4F_7N concentration is relatively gradual.

Comparison of HFO(E)/CO_2 gas mixture[8]

HFO(E)/CO_2 gas mixture exhibited a linear-saturation rising pattern with both mixing ratio and gas pressure, mirroring the trend observed in SF_6 when the HFO(E) gas concentration ranged between 25% and 30%. The HFO-butene/ CO_2 with low HFO-butene content and gas pressure, which is ascribed to the shielding effect of the stable “space charge layer” nearby the needle electrode that improves the non-uniformity of the electric field. The corresponding results revealed the PD characteristics of HFO-butene/ CO_2 gas mixture. The HFO(E) and CO_2 gas mixture have equivalent break down and PD insulation strength to SF_6 at a pressure range of 0.15

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MPa. Therefore, the findings of this research conclude that the HFO(E)- CO_2 gas mixture, more precisely (30/70)% ratio, can successfully substitute SF_6 gas in medium voltage gas insulated switchgear applications. The partial discharge characteristics were conducted using the UHF method for PD inception and extinction voltages.

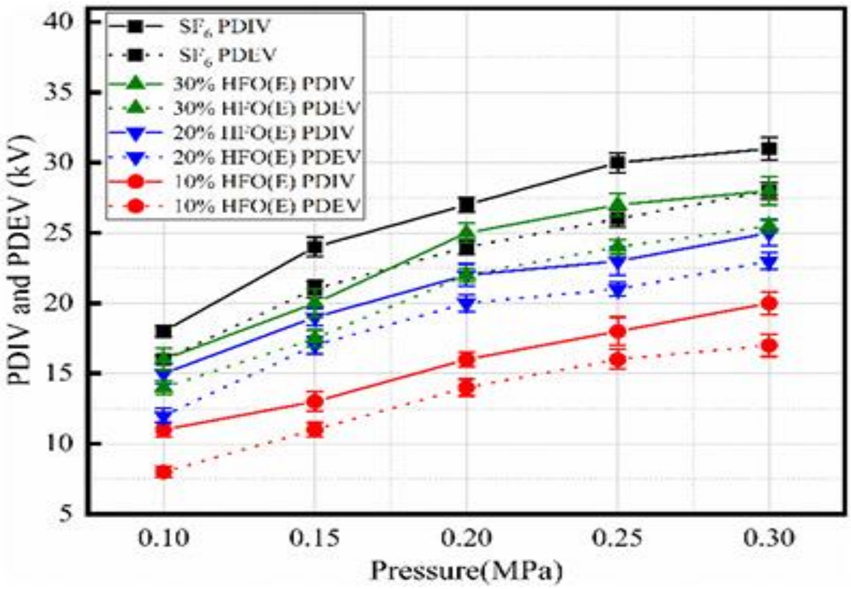

Fig 2.6.1: PDIV and PDEV of HFO(E) and CO2 gas mixture.

An important parameter known as partial discharge extinguishing voltage PDEV defines the difficulty of gas mixture PD extinction. PDEV is typically less than PDIV; the higher PDEV value of the gas mixture indicates the challenges associated with PD extinguishing. In conjunction with SF_6 gas, Figure shows the HFO(E)andCO2 PDIV and PDEV properties for various mixing ratios at different pressure levels. It has been noted that the SF_6 PDIV and PDEV difference between 0.1 and 0.3 MPa is nearly constant at 3 kV. However, the difference between HFO(E) and CO_2 obtained for 10 % HFO(E) is averaged at 2.4 kV; for 20%, it is 2.2 kV, and for 30%, the difference is 2.8 kV. It is important to note that the difference between the gas mixture's PDIV and PDEV is not significantly affected by changing the mixing ratio of HFO(E) content.

Comparison of Pd_3-TiO_2(101)[5]

Comparing with the intrinsic anatase TiO_2 (101) surface, the energy gap of the Pd3-dopedanatase TiO_2 (101) surface decreases dramatically, signifying an increase of conductivity. Based on the conductivity change of adsorption structures, Pd3- TiO_2 (101) can effectively distinguish the type and concentration of SOF2 and SO2F2. Therefore, the Pd3-doped TiO_2 (101) surface can be applied in the development of sensing material for gas detection.

CONCLUSION

- Firstly, SF6/N2 gas mixture can not only reduce the consumption of SF6 in power system, but also effectively alleviate SF6 greenhouse effect and solve the problem of high liquefaction temperature.
- While studying SF_6 / CO_2 the particle contamination in CO_2 are the major cause for the partial discharges which in turn cause the insulation failure. Because CO_2-SF_6 gas mixture was not good in arc interruption. As the voltages were increased near breakdown the arc persisted in all the experiments conducted. Therefore CO_2-SF_6 gas mixture may not be feasible to be used in circuit breakers which needs better arc interruption properties.
- The research, so far, into alternative gases has shown that CF3I mixtures exhibit promising breakdown characteristics comparable to those of SF6 gas based on the measured 50% breakdown voltage.
- As the partial pressure of $C_5F_{10}O$ increases, the relative insulation strength increasing trend of the $C_5F_{10}O$ gas mixtures. The AC breakdown voltage of $C_5F_{10}O$ /Air gas mixture is higher than that of

$C_5F_{10}O$ /N2 gas mixture under the same conditions. $C_5F_{10}O$ has a high liquefaction temperature (26.9C) at normal pressure, its dielectric strength reaches twice that of SF6. The Global Warming Potential (GWP) value of $C_5F_{10}O$ is only 1 and its atmospheric lifetime is about 15 days.$C_5F_{10}O$ (C5 per uorinatedketone) has received extensive attention due to its great insulation and eco-friendly performance, which has the potential to replace SF6 usage in power industries.

- Due to the relatively lower stability of C_4F_7N compared to SF6, ionization and decomposition may occur under discharge or overheating conditions. C_4F_7N has emerged as one of the most promising eco-friendly insulating gases. The power frequency breakdown voltage of pure C_4F_7N is approximately twice that of SF6, while its GWP is 2100, significantly lower than that of SF6. In practical applications, to reduce the liquefaction temperature of C_4F_7N, it is often mixed with buffer gases such as N_2, CO_2, or dry air, which further reduces the GWP of the gas mixture.
- This paper conclude that the HFO(E)-CO_2 gas mixture, more precisely (30/70)% ratio, can successfully substitute $SF_{6.}$ gas in medium voltage gas insulated switchgear applications. The HFO-butene/ CO_2 with low HFO-butene content and gas pressure, which is ascribed to the shielding effect of the stable "space charge layer" nearby the needle electrode that improves the non-uniformity of the electric field.
- Due to the high specific surface area, high symmetry, electronic properties, and other outstanding advantages of TiO_2 nanotubes, it has become a research hotspot as gas detection material, and shows broad application prospect. Noble metal doping on TiO_2 nanotubes surface has proven to be able to narrow the energy gap, and enhance the gas-sensing ability to specific gas molecules

By studying different dielectric properties of different insulating gases and gas mixtures as an alternative to $SF_{6.}$ All the gases exhibit some partial discharge characteristics in a good manner some dielectrics having poor properties to exhibit partial discharge characteristics.

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