Emerging Eco-Friendly Alternatives to SF_6 for High Voltage Insulation: A Review

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ABSTRACT

Sulphur hexafluoride (SF_6) has been extensively utilized as an arc-quenching and insulating gas in high-voltage apparatus including gas-insulated switchgear (GIS), circuit breakers, and transformers because of its high dielectric strength and thermal stability. SF_6 is a very powerful greenhouse gas with a very high global warming potential (GWP ≈ 23,500) and atmospheric lifetime (~3200 years), which makes its future use environmentally unsustainable. In turn, studies have focused more intensely on substitute gases with comparable insulation qualities but much lower environmental footprint. Of the likely candidates, hydrofluorocarbons (HFCs) HFC-227ea (C_3HF_7) and HFC-125 (C_2HF_5) have been increasingly receiving attention. The present review offers a thorough appraisal of the physical, chemical, thermal, and environmental properties of HFC-227ea and HFC-125 in comparison with SF_6 and other future alternatives such as C_4F_7N and CO_2. The major performance parameters such as dielectric strength, liquefaction temperature, boiling point, GWP, electrical conductivity at different temperatures, and partial discharge (PD) characteristics are thoroughly examined. The results indicate that HFC-227ea and HFC-125 have good insulation properties with dielectric strength from 0.5 to 0.7 times that of SF_6, no ozone depletion potential (ODP), and significantly lower GWPs (2900 and 3500, respectively). Both gases exhibit minimal conductivity at operational temperatures, satisfactory thermal stability, and good compatibility with PD measurement methods. Although not direct replacements, these gases may serve as viable options for medium-voltage or mixed-gas systems under carefully controlled conditions. The study concludes that HFC-227ea and HFC-125 hold significant potential for contributing to the development of environmentally sustainable high voltage insulation technologies.

Keywords: HFC227ea (Heptafluoropropane), HFC125 (Pentafluoroethane), Global Warming potential (GWP), SF_6(Sulfur hexafluoride) and dielectric breakdown.

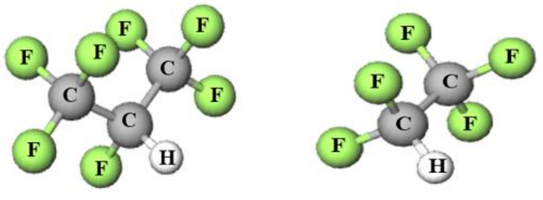
INTRODUCTION

Sulfur hexafluoride (SF_6) is a colorless, odorless, non-flammable, non-poisonous and highly electronegative gas with outstanding dielectric performance, rendering it invaluable as an insulating and arc-extinguishing medium in high-voltage electrical equipment, including circuit breakers and switchgear. SF_6's density and chemical stability are the reasons for its outstanding performance in electrical insulation and current interruption. But with its extensive usage comes serious environmental implications. SF_6 is the strongest greenhouse gas, with a Global Warming Potential (GWP) about 23,500 times higher than carbon dioxide over 100 years [1], [2]. Its atmospheric lifetime of about 3,200 years enables it to build up and remain in the atmosphere, thus making a considerable contribution towards long-term climate change in spite of relatively low atmospheric concentrations. In addition, the electrical breakdown of SF_6 leads to the formation of several toxic decomposition products containing fluorine. SF_6 being classified as a regulated gas under the third Framework, the 2016 Paris (France) Agreement calls for zero greenhouse gas emissions in the second half of the century. As a result, identifying alternative insulating gases with comparable or superior dielectric strength and significantly lower GWP has become a major focus of current research. Due to its high GWP and environmental effects, SF_6 emissions are controlled under global accords like the Kyoto Protocol and California Air Resources Board (CARB) [3]. As a result, the development and evaluation of eco-friendly insulating gases with comparable dielectric strength have become a prominent focus in high-voltage power system research [4].

Numerous studies have been carried out to identify environmentally friendly alternatives to SF_6, a gas known for its excellent dielectric and arc-quenching properties but also for its extremely high GWP. The potential substitutes are generally classified into three main categories. (i) Traditional gases and their mixtures with SF_6, including air, nitrogen (N_2), and carbon dioxide (CO_2), are abundant, non-toxic, and eco-friendly. When blended with SF_6, these gases help reduce its concentration while maintaining acceptable insulation performance. (ii) Fluorocarbons and halogenated gases such as tetrafluoromethane (CF_4), trifluoroiodomethane (CF_3I), octafluorocyclobutane (c-C_4F_8), and notably hydrofluorocarbons (HFCs) like HFC-227ea (C_3HF_7) and HFC-125 (C_2HF_5), have attracted attention due to their relatively good dielectric properties and moderate arc-quenching ability. Although most of these gases, particularly HFC-227ea and HFC-125, have been primarily applied in medium-voltage (MV) systems, their binary and ternary gas mixtures are now being investigated for possible extension to high-voltage (HV) insulation systems. The goal is to achieve a balance between dielectric strength and environmental impact, especially since these HFCs offer significantly lower GWPs compared to SF_6. (iii) New fluorinated compounds, including perfluoronitriles (PFNs) such as C_4-PFN [$(CF_3)_2CFCN$] and perfluoroketones (PFKs) like C_5-PFK [$CF_3COCF(CF_3)_2$], show strong potential as long-term SF_6 substitutes. These compounds are of particular interest due to their low GWP, good insulation characteristics, and compatibility in gas mixtures designed for gas-insulated switchgear (GIS) and other high-voltage applications. The Key Properties of SF_6 and Its Potential Alternative Insulating Gases are given in Table 1. This review focuses on the evaluation of HFC-227ea, HFC-125, and their mixtures as eco-friendly insulation alternatives to SF_6, supported by conceptual analysis and comparative graphical representation of their key characteristics.

OVERVIEW Of HFC-227ea and HFC-125

To assess the viability of HFC-227ea (C_3HF_7) and HFC-125 (C_2HF_5) as substitutes for SF_6 in HV electrical applications, their physical, environmental, and safety attributes must align with essential performance and eco-friendliness standards [5]. The critical evaluation parameters include GWP, relative dielectric strength (E_r), liquefaction temperature (T_b), arc quenching capability, chemical stability, and compatibility with HV equipment design. The hydrofluorocarbon HFC-227ea is categorized as a saturated fluorinated alkane and has the chemical formula C_3HF_7. 1,1,1,2,3,3,3-heptafluoropropane is its IUPAC name [6]. Fig. 1(a) shows the molecular structure of three carbon atoms, seven fluorine atoms, and one hydrogen atom make up the molecular structure, which is symmetrical and saturated. Strong molecular stability brought about by this high fluorination level produces exceptional chemical and thermal resistance. Because of these qualities, HFC-227ea is a good choice for HV insulation applications where safety and dielectric dependability under electrical stress are essential. The hydrofluorocarbon HFC-125, which has the chemical formula C_2HF_5, is a member of the saturated fluorinated alkanes class. Pentafluoroethane is its IUPAC name. The molecule is made up of one hydrogen atom, five fluorine atoms, and two carbon atoms bound together as shown in Fig. 1(b). Strong C–F bonds and a compact, symmetrical configuration are features of this structure that support its thermal stability and chemical inertness. HFC-125 is regarded as a good substitute for SF_6 in high-voltage electrical equipment insulation because of its good dielectric properties and moderate boiling point. Hydrofluorocarbons (HFCs), which do not destroy the ozone layer but do contribute to global warming, include HFC-227ea and HFC-125. With a GWP of roughly 2900 over a 100-year time horizon, HFC-227ea is 3500 times more effective than CO_2 at trapping heat. Compared to natural gases, HFC-125 has a high climate impact despite having a slightly lower GWP of about 3500. Both HFCs are relatively more climate-friendly because these values are significantly lower than those of SF_6, which has a GWP of over 23,500.



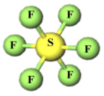
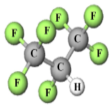
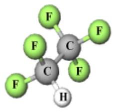
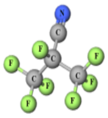
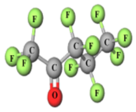
a

b

Fig. 1. Molecular structures of (a) HFC-227ea (C_3HF_7) and (b) HFC-125 (C_2HF_5)

The zero ODP of HFC-227ea and HFC-125 is one of their main environmental benefits. These HFCs are not composed of chlorine or bromine atoms, which are the main cause of stratospheric ozone depletion, in contrast to chlorinated or brominated compounds (such as CFCs and HCFCs). Because of this, both gases are ozone safe according to international environmental standards like the Montreal Protocol.

TABLE I Key Properties Of SF_6 And Its Potential Alternative Insulating Gases

Chemical formula	**Molecular structure**	**GWP (100 years)**	**Atmospheric lifetime**	**Liquefaction temperature (°C)**	**Dielectric strength relative to SF_6 $(E/N)_{crit}$**	**Molecular Weight (g/ml)**	**Boiling point (^{0}C)**	**Vapor pressure at 25^0 C (kPa)**	**Density kg/m^3 at std Pressure**
SF_6		23500	3200a	-63.8	1	146.06	-63.8	2130	6.17
HFC227ea (C_3HF_7)		2900	34a	-16.7	~0.45-0.6	170.03	-16.7	~391	6.5
HFC125 (C_2HF)		3500	29a	-48.1	~ 0.5 –0.7	120.02	-48.1	~570	~5.0
C_4F_7N		2090	22a	−4.7°C	2.2	195.06	−4.7°C	~200	~6.7
C_4F_8		8700	3220a	−6.3°C	1.27	200.4	−6.3°C	~275	~8.1
$C_5F_{10}O$		<1	15	+27°C	1.4	316.04	+27°C	~20	~13.6

Under typical operating conditions, HFC-227ea and HFC-125 both demonstrate exceptional thermal and chemical stability, which is crucial for their application in high-voltage power equipment. Within typical operating temperature ranges, HFC-125 exhibits minimal deterioration in insulating behavior and high thermal endurance. They are appropriate for the harsh conditions commonly found in GIS because of their thermal robustness. With LC_{50} (Lethal Concentration, 50%) values significantly above critical thresholds, both gases are considered to be non- toxic and have low acute toxicity, suggesting a broad safety margin for occupational exposure. According to ASTM and ISO fire testing standards, HFC-227ea is rated as non-flammable, whereas HFC-125 is categorized as slightly flammable (ASHRAE safety group A1) but poses little risk of combustion under normal equipment conditions. Unless exposed to severe arcing, which can result in the formation of some hazardous breakdown products (like HF), both gases are chemically stable and inert in electrical environments. This risk also exists for SF_6 and other halogenated gases. The selection of HFC-227ea and HFC-125 as potential substitutes for SF_6 in HV insulation systems is influenced by a blend of environmental, electrical, and safety-related factors. These gases possess properties that position them as viable alternatives to SF_6, which, despite its superior performance, poses significant environmental challenges due to its extremely high GWP.

Evaluation Of Key Performance Parameters

It is crucial to analyze the basic physical and electrical performance characteristics of HFC-227ea and HFC-125 to ascertain whether they are suitable replacements for SF_6 in HV insulation applications. Physical properties (density and boiling point), dielectric strength, arc-quenching capabilities, and behavior under partial discharge (PD) conditions are among the important parameters that are compared in this section.

Physical Properties

The fundamental physical characteristics of insulating gases are crucial because they have a direct impact on the gas's functionality, safety, environmental impact, and practicality in high-voltage electrical systems [7]. All the gases under consideration exhibit very good electrical insulation and very little conductivity at low temperatures, about 300 K. But as temperatures rise, especially while arcing is occurring, gases like CO_2 and N_2 become more conductive because of ionization, which reduces their ability to put out arcs. On the other hand, because of its strong electron affinity and fast recombination properties, SF_6 shows a minor increase in conductivity while maintaining good arc quenching ability. Unless utilized in optimum gas combinations, alternative gases such as HFC-227ea, HFC-125, and C_4F_7N have a small increase in conductivity at high temperatures, although they typically lesser arc suppression capabilities than SF_6. All gases demonstrate extremely low electrical conductivity at lower temperatures (below 3000 K), which is significant to typical HV operating conditions and validates their insulating properties. Compared to SF_6, HFC-227ea and HFC-125 exhibit lower conductivity, indicating better insulation performance. While CO_2 and N_2 exhibit comparatively higher conductivity, which makes them less appropriate as stand-alone insulating media, C_4F_7N also performs well as shown in Fig. 2. All gases become more thermally conductive as the temperature rises. N_2 has the highest thermal conductivity of all of them, whereas SF_6, HFC-227ea, HFC-125, and C_4F_7N have comparatively lower values as shown in Fig. 3. These fluorinated gases' reduced thermal conductivity, which restricts heat transfer and improves dielectric stability under thermal stress, supports their applicability for HV insulation applications.

Dielectric Strength

Although SF_6 is superior in terms of dielectric strength, arc quenching, and partial discharge resistance, its exceptionally high GWP renders it unsuitable for environment.

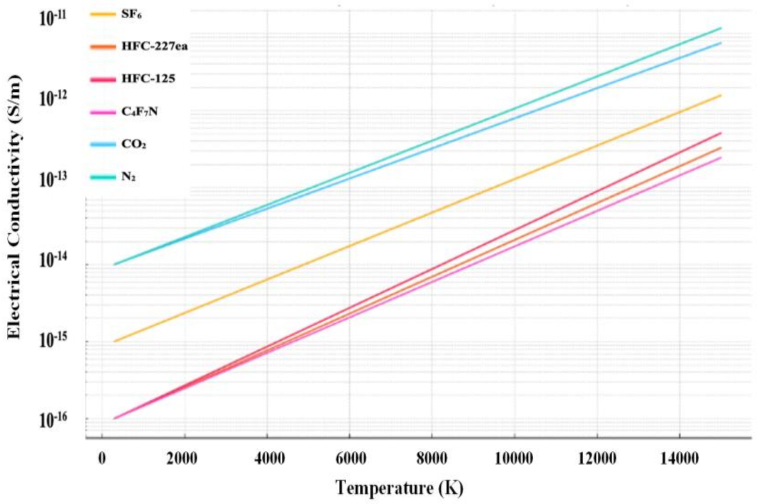


Fig. 2. Conceptual representation of the electrical conductivity of various insulating gases Vs. temperature

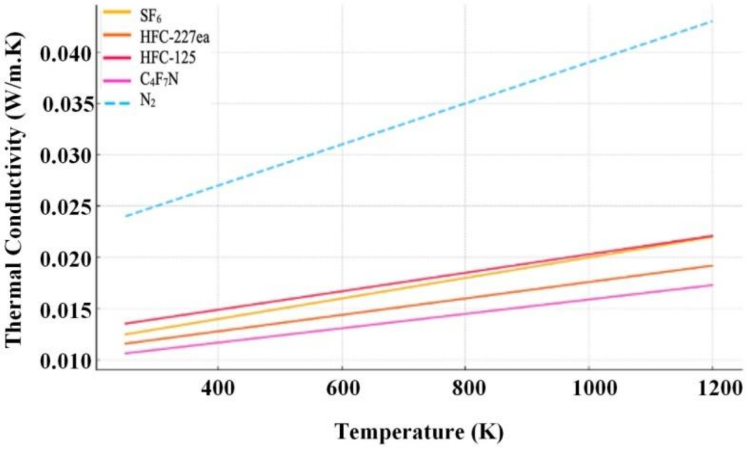


Fig. 3. Conceptual representation of the thermal conductivity of various insulating gases Vs. temperature

HFC-227ea and HFC-125 are stable, non-flammable, and their application in colder climates or in situations requiring pressurization may be restricted due to their higher boiling points and noticeably lower vapor pressure. From Fig. 4, because of its remarkable dielectric strength of about 95 kV/cm and low boiling point of -63.8°C, SF_6 is widely used in high-voltage insulation [8]. The graph compares the dielectric strength and boiling point of several gases that were considered as substitutes for SF_6. Among environmentally friendly alternatives, HFC-227ea, which has a boiling point of -16.7°C, and HFC-125, which has a boiling point of -48.1°C, exhibit moderate dielectric strengths of roughly 50 kV/cm and 45 kV/cm, respectively. Their blend (HFC-227ea + HFC-125) performs similarly to HFC-227ea, indicating the possibility of creating customized mixtures. Despite lacking the dielectric strength of SF_6, these HFCs are promising alternatives due to their zero ODP and significantly lower GWP. Other options with high dielectric strengths between 70 and 80 kV/cm include C_4F_8, C_4F_7N, and $C_5F_{10}O$ [9]. Although the GWP values of both HFC alternatives are lower than those of SF_6, they are still high, and at arc circumstances, their breakdown can result in hazardous byproducts like hydrogen fluoride (HF). Whereas the atmospheric lifespan of a gas is a key environmental indicator, as it determines how long it persists in the atmosphere and its contribution to global warming potential. This makes it a significant factor in climate considerations, especially for gases like SF_6, which has an exceptionally long lifetime of nearly 3,000 years and poses a substantial long-term climate risk.

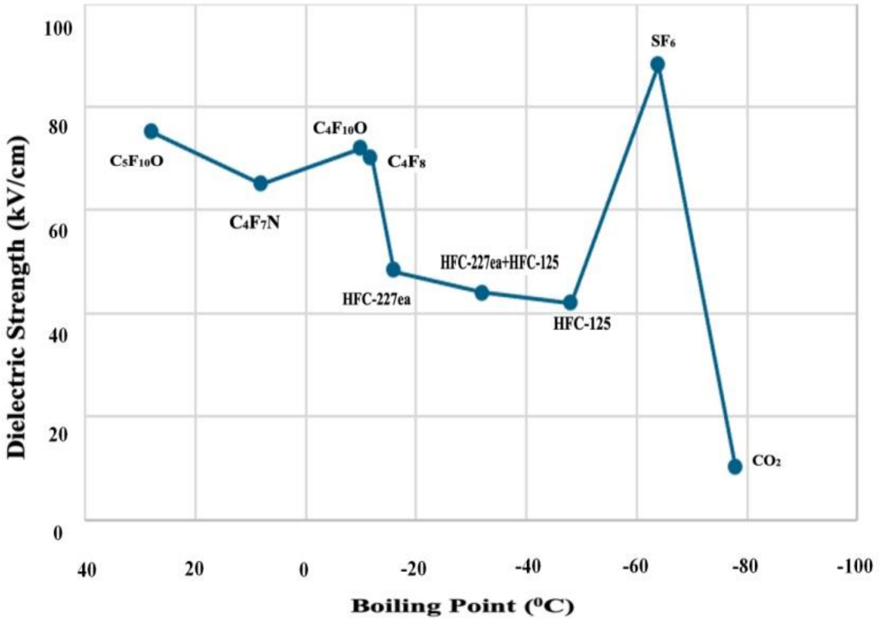


Fig. 4. Dielectric strength of various gases as a function of their liquefaction points

Consequently, there is a push for alternatives with shorter lifespans and reduced environmental impact, such as HFC-227ea and HFC-125, which are considered despite their own GWPs, as they degrade faster than SF_6. The relationship between dielectric strength and pressure for SF_6 and a number of alternative gases is as shown in Fig. 5.

At every pressure level, SF_6 exhibits the highest dielectric strength, followed by C_4F_8 and C_4F_7N. Among the substitutes, HFC-227ea and HFC-125 have a moderate dielectric strength, and their combination performs better. Significantly lower values are shown for CO_2, air, and N_2, confirming their limited applicability as stand-alone insulating media in high-voltage applications. Liquefaction (condensation at moderate pressure and temperature) is a critical parameter influencing the applicability of insulating gases, particularly in cold climates. Gases with a higher tendency to liquefy at low temperatures may condense within GIS/GIL systems, thereby compromising insulation performance and system reliability.

SF_6 demonstrates excellent behavior in this regard, exhibiting a low risk of liquefaction across a broad temperature range. However, alternatives like HFC-227ea and HFC-125 are more susceptible to liquefaction at lower temperatures, necessitating the use of gas mixtures or pressure adjustments to ensure stable performance. Molecular weight plays a significant role in determining the physical behavior and electrical performance of insulating gases. Gases with heavier molecules and complex structures generally have lower thermal conductivity due to limited vibrational and translational energy transfer. Gases with higher molecular weight tend to exhibit better dielectric strength due to increased density, which enhances their ability to suppress electrical discharges. However, high molecular weight can also lead to heavier gas handling requirements and may affect gas flow dynamics in large-scale equipment. SF_6, with a molecular weight of approximately 146 g/mol, strikes a balance between performance and manageability. In comparison, HFC-227ea (~170 g/mol) has a higher molecular weight, contributing to its strong insulation characteristics, while HFC-125 (~120 g/mol) is relatively lighter, potentially offering better flow properties but slightly reduced dielectric performance.

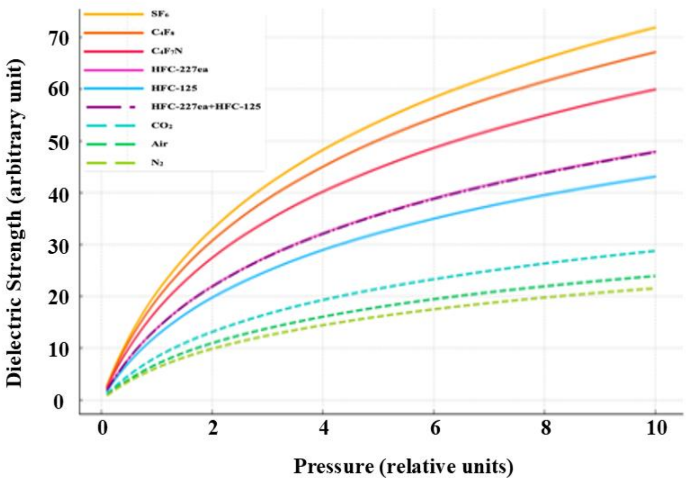


Fig. 5. Variation of Dielectric Strength of SF_6 and its alternatives as a function of Pressure

These differences influence how each gas behaves under high-voltage conditions and impact their suitability for various insulation system designs. Density is a crucial parameter influencing the insulation strength and arc-quenching capability of gases used in HV systems. Higher gas density typically enhances the dielectric performance by reducing the mean free path of electrons, thereby limiting electrical breakdown. SF_6, with a density of approximately 6.17 kg/m³ at 25 °C and 1 atm, provides excellent insulation and is a benchmark for comparison. HFC-227ea has a slightly higher density (~6.5 kg/m³), offering comparable dielectric properties, whereas HFC-125 has a moderate density (~5 kg/m³), which may lead to marginally reduced insulation performance. While increased density can be beneficial electrically, it also affects the design of gas handling systems and pressurization requirements. Therefore, optimizing gas density is essential for achieving reliable and efficient performance in GIS/GIL applications.

Arc Quenching

SF_6 is widely used for its excellent insulation and arc-quenching properties, but due to its extremely high GWP (~23,500× CO_2), finding eco-friendly alternatives has become essential. The basic premise is that potential replacement gases should exhibit liquefaction temperatures and insulating strengths that are on par with or superior to those of SF_6. A lower liquefaction point is desirable in gaseous insulation systems because it ensures that the gas remains in the vapor phase, maintaining reliable dielectric properties, system stability, and safety across a wide range of operating temperatures and pressures. Compared to SF_6, these new insulating gases such as HFC-227ea, HFC-125, C_4F_7N, C_4F_8, $C_5F_{10}O$ have significantly lower GWP, but their higher liquefaction temperatures require mixing with buffer gases, often at the cost of reduced insulation performance. Among these new gases C_4F_7N, C_4F_8, $C_5F_{10}O$ are having high liquefaction temperatures than HFC-227ea, HFC-125. For instance, HFC-227ea has a relatively high liquefaction temperature of -16.7 °C, requiring the use of buffer gases. Alongside traditional options like CO_2 and N_2, HFC-125 another refrigerant with a lower liquefaction temperature of -48.1 °C is often chosen to enhance the dielectric strength of the gas mixture. Given the vast range of potential gas mixes, it is crucial to set clear standards in order to identify the best substitutes for SF_6 for certain uses. Arc quenching capability is one of the most important factors for assessing the efficacy of possible replacement gases.

During the arc quenching process, the arc's temperature initially drops sharply, leading to a rapid release of arc energy. As the gas cools, it begins to capture free electrons from the arc plasma, causing a significant decrease in arc conductivity. With more electrons being absorbed, the insulating properties of the gas gradually restore. Eventually, the gas temperature stabilizes near room temperature, fully regaining its dielectric strength. An essential component of gaseous insulation systems' interruption performance is the arc quenching procedure. Following an arc discharge, it takes place in a number of distinct phases [10], each of which helps to restore the gas's insulating qualities: (i) Thermal Recovery Stage**:** The arc has very high temperatures at the beginning of the arc quenching process, frequently reaching several thousand Kelvin. A large amount of this thermal energy is absorbed by gases like SF_6, C_4F_7N, or their substitutes. This quick absorption causes the arc temperature to drop drastically, which starts the arc energy dissipation process. The thermal energy required to maintain ionization decreases as the gas cools the arc. As a result, the ionization processes become weaker, paving the way for later dielectric recovery and electron attachment. (ii) Pre-Dielectric Recovery Stage**:** The gas starts to absorb or grab free electrons from the arc plasma as it cools down. The breakdown of the conductive path is aided by the noticeable drop in arc conductivity brought on by this significant decrease in free electron density. (iii) Post-Dielectric Recovery Stage**:** The gas's dielectric strength is greatly increased during this phase as additional electron attachment proceeds. Making sure the gas can resist the recovery voltage and avoid re-ignition requires this step. (iv)Residual-Gas Cooling Stage**:** Ultimately, the gas keeps cooling until it reaches room temperature, or ambient temperature, which is usually approximately 300 K. The gas has completely recovered its initial insulating qualities by the end of this phase. The current interruption process in a disconnector can be divided into two distinct stages: the arcing phase and the post-arc phase. During the arcing phase, as the contacts begin to separate, an arc forms and is sustained between them. This arc is expected to extinguish when the alternating current reaches the current zero (CZ) point [11]. As the arc current decays to zero, the energy injected into the arc also diminishes, resulting in a decrease in arc temperature and conductance. Consequently, the arc column starts to shrink. However, even after the CZ point, the arc plasma remains hot, and the conductive state is briefly maintained. During this transition, the recovery voltage starts to build across the contact gap. Due to the residual ionization and high plasma temperature, a small current called the post-arc current continues to flow through the gap.

The ability of the insulating gas to withstand this post-arc phase without reignition is crucial to ensure successful current interruption. The key determinant of a gas’s interruption capability is its resistance to re-ignition after CZ. If the energy injected by the post-arc current into the arc gap exceeds the rate of energy dissipation, the plasma temperature rises, increasing arc channel conductance. This can cause the post-arc current to escalate, leading to arc reignition. Conversely, if energy dissipation dominates, the post-arc current gradually decays to zero, and the interruption process completes successfully.

Partial Discharge

According to the International Electrotechnical Commission (IEC) 60270 technical standard titled "High-Voltage Test Techniques-Partial Discharge Measurements", PD is defined as “A localized electrical discharge that only partially bridges the insulation between conductors, and which may or may not occur adjacent to a conductor” [12]. PD are brief current or voltage pulses that occur within insulation systems when the electric field exceeds the dielectric's breakdown strength locally, without causing a complete failure. The characteristics of these pulses such as amplitude, duration, and repetition rate are significantly influenced by the applied voltage (Ua), which determines the electric field intensity. The type and condition of the dielectric material, including its thickness, moisture content, and defects (e.g., voids or impurities), also play a critical role in PD inception and severity. Surrounding environmental factors, such as temperature, humidity, and pressure, further affect the dielectric's behavior and the PD patterns, making these variables key considerations in insulation design and monitoring. The main causes of PD as noted include surface contamination and irregularities in solid insulation, which can create localized areas of reduced dielectric strength. Voids formed within the solid insulation during manufacturing act as weak points where electric fields can intensify, leading to PD. Additionally, cracks in the insulation resulting from mechanical breakdown provide pathways for discharge activity. These factors collectively contribute to the initiation and propagation of PD, affecting the insulation's reliability.

Partial discharge types

PD are generally categorized into three main types: surface discharges, internal discharges (including cavity and treeing discharges), and corona discharges. Surface Discharges: These discharges develop along the surface of insulating materials, often triggered by contaminants, moisture, or surface imperfections that create a partially conductive path. When the electric field across the surface reaches a critical level, localized discharges are initiated. Surface discharges are commonly observed in components like bushings and insulators in high-voltage systems and can result in insulation degradation through erosion or tracking over time.

Internal Discharges (Cavity and Treeing): These discharges occur inside insulating materials, typically within air gaps or voids that may form due to manufacturing defects or insulation aging. Cavity discharges arise when the electric field within these voids surpasses the breakdown threshold of the enclosed gas, leading to repetitive discharges. Treeing is a form of degradation where the insulation deteriorates in a branching pattern over time, driven by continued partial discharges, ultimately resulting in insulation failure. The assessment of PD characteristics in high-voltage equipment relies on several quantitative parameters that reveal the severity of PD activity and the condition of the insulation system. These parameters are critical for diagnosing early degradation and preventing insulation failure: (i) PD Inception Voltage (U_i): This is the minimum voltage level at which partial discharges initiate within the insulation. It reflects the dielectric system's threshold for breakdown under electrical stress. A lower U_i typically indicates insulation defects, aging, or contamination, making it a key diagnostic parameter. (ii) Accumulated Apparent Charge (q_a): Represented in picocoulombs (pC), this parameter quantifies the total charge involved in PD events over a specified time. It indicates the intensity and frequency of discharges, with higher q_a values suggesting significant insulation degradation. (iii) Cumulative Energy: It denotes the total energy dissipated due to PD activity over time. It provides insight into the long-term stress imposed on the insulation system, aiding in the prediction of potential breakdown or failure. (iv) Average Discharge Current (I): This is the mean value of discharge current pulses recorded over a period. It correlates with both the frequency and intensity of PD events and serves as an indicator of ongoing insulation stress. (v) Discharge Power (P): Defined as the time-averaged product of instantaneous voltage and current, discharge power illustrates the rate at which PD energy is released into the insulation. Elevated power levels point to aggressive degradation mechanisms. (vi) Quadratic Rate (D): The quadratic rate captures the rate of increase in discharge magnitude or energy dissipation over time. As a nonlinear parameter, it is particularly useful for tracking the acceleration of insulation deterioration processes.

Corona discharges: Corona discharges happen when the electric field strength surrounding a high-voltage conductor becomes greater than the gas surrounding it, such as air, and has a threshold of ionization, most pronounced at points, sharp edges, or rough spots where the electric field is in focus. Once the field intensity exceeds a critical value of about 30 kV/cm for air at normal pressure, it causes partial ionization of air atoms and molecules, producing a weakly conducting plasma that appears as a soft bluish glow, usually heard as hissing or crackling in dim light. Although less than complete electrical breakdowns such as arc discharges, corona is unwanted in high voltage use since it can slowly break down insulation, lead to losses in power, and initiate chemical reactions in air, forming ozone (O_3) and nitrogen oxides (NO_x), which further promote aging of insulating materials. This phenomenon is often seen in overhead transmission lines, high-voltage bushings, transformer terminals, and gas-insulated switchgear (GIS) systems, especially during wet or contaminated conditions. To prevent corona, engineers adopt design methods including smoothing conductor surfaces, using rounded terminals such as corona rings, and using insulating gases with increased dielectric strength.

Partial Discharge Monitoring Techniques

Partial discharge (PD) activity can be effectively monitored by detecting various physical phenomena generated during discharges, such as heat, acoustic vibration, light emission, gas decomposition, and electromagnetic radiation [13]. These manifestations are captured using a range of sensors, including electrical sensors (for current or voltage pulses), thermal sensors (for heat signatures), and chemical sensors (for gas byproducts), as outlined in available research. The monitoring and analysis process typically follows three main stages: Detection of PD Signals: In this initial phase, suitable sensors are deployed to capture PD activity. Electrical detectors sense transient pulses, thermal cameras or infrared sensors identify heat anomalies, and chemical sensors detect insulating material degradation through the presence of reactive gases. Feature Extraction: Once signals are captured, they undergo signal processing to extract relevant features. Parameters such as PD inception voltage, apparent charge magnitude, discharge repetition rate, and pulse shape are isolated using techniques like Fast Fourier Transform (FFT), wavelet analysis, or Hilbert-Huang transforms. This step is crucial for quantifying discharge characteristics and assessing insulation health. Representation of PD Signals: Extracted features are then visualized in forms such as time-domain waveforms, frequency spectra, or phase-resolved partial discharge (PRPD) patterns. Statistical tools like Weibull or Gaussian distributions are also used to interpret PD behavior. These visual and statistical representations provide insights into the type and severity of insulation defects, aiding in predictive maintenance and fault diagnostics.

Additionally, each type of PD defect (e.g., surface, internal, corona) exhibits unique patterns and behaviors, characterized by specific features extracted from the raw PD data [14]. This pre-processing transforms raw signals into a set of discriminatory identifiable features, enhancing fault detection and localization in high-voltage equipment (HVE). The quantification of statistical features (e.g., mean, variance), time-resolved PD (TRPD) features (e.g., pulse timing), and phase-resolved PD (PRPD) features (e.g., phase-angle distribution) from multiple PD defects is processed using advanced mathematical tools. These include Distance classifier (k-NN), Neural Network (NN), Support Vector Machine (SVM), Pulse Sequence Analysis (PSA), fuzzy logic, and decision function classifiers, which employ clustering or classification to separate PD defects, improving diagnostic accuracy.

CONCLUSIONS

The quest for green alternatives to sulfur hexafluoride (SF_6) has emerged as a high priority owing to its very high global warming potential and long atmospheric lifetime. Hydrofluorocarbons like HFC-227ea and HFC-125 are some of the likely candidates that have shown promise to replace SF_6 in high-voltage (HV) insulation applications. The present review has systematically compared their major physical, chemical, dielectric, and thermal properties with SF_6 and other environmentally friendly gases. Both HFC-227ea and HFC-125 have low electrical conductivity at operating temperatures, acceptable dielectric strength, and desirable liquefaction and boiling point values, making them appropriate for HV equipment. Their zero ODP and much lower GWP than SF_6 also make them more environment friendly. Additionally, their thermal stability, lack of flammability, and chemical inertness under normal conditions guarantee sound performance and operational safety. But some challenges persist. Their dielectric strength is below that of SF_6, and increased operating pressure or application in gas mixtures could be required to achieve SF_6 performance. Additional study is required to assess long-term aging characteristics, materials compatibility, arc quenching characteristics under fault conditions, and cost-performance trade-offs. In summary, HFC-227ea and HFC-125 are technically feasible and more environmentally friendly substitutes for SF_6 in gas-insulated equipment, particularly for medium-voltage and certain high-voltage applications. Further experimental and simulation research will be critical to ensure that they are completely validated for use and to enable a transition toward more environmentally friendly insulation technologies.

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