Green Gas for Grid as an Eco-Friendly Alternative Insulation Gas to SF$_6$: A Review

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Featured Application: Insulation design of gas-insulated electrical power facilities using eco-friendly green gas for a grid (g3) to replace SF$_6$ that causes environmental concerns.

Abstract: This paper deals with a review of the state-of-the-art performance investigations of green gas for grid (g3) gas, which is an emerging eco-friendly alternative insulation gas for sulfur hexafluoride (SF$_6$) that will be used in gas-insulated power facilities for reducing environmental concerns. The required physical and chemical properties of insulation gas for high-voltage applications are discussed, including dielectric strength, arc-quenching capability, heat dissipation, boiling point, vapor pressure, compatibility, and environmental and safety requirements. Current studies and results on AC, DC, and lightning impulse breakdown voltage, as well as the partial discharge of g3 gas, are provided, which indicate an equivalent dielectric strength of g3 gas with SF$_6$ after a proper design change or an increase in gas pressure. The switching bus-transfer current test, temperature rise test, and liquefaction temperature calculation also verify the possibility of replacing SF$_6$ with g3 gas. In addition, the use of g3 gas significantly reduces the aforementioned environmental concerns in terms of global warming potential and atmosphere lifetime. In recent years, g3 gas-insulated power facilities, including switchgear, transmission line, circuit breaker, and transformer, have been commercially available in the electric power industry.

Keywords: green gas for grid (g3); eco-friendly insulation gas; SF$_6$ alternative; gas-insulated power facilities; dielectric strength; global warming potential (GWP)

1. Introduction

Sulfur hexafluoride (SF$_6$) has been used as the most popular insulation gas in gas-insulated power facilities, such as switchgear (GIS), circuit breaker (GCB), transmission line (GIL), and transformer (GIT), since 1947. This is because SF$_6$ has an exceptional combination of physical and chemical properties for high-voltage applications, including high-dielectric strength (three times that of air at atmospheric pressure), arc-quenching capability, thermal conductivity, thermal stability, nonflammability, nontoxicity, nonexplosive, and chemical inertness [1–4]. As a result, SF$_6$-insulated equipment can be designed with reduced size, high reliability, and economic efficiency [5,6]. It is widely employed in space-limited locations such as city substations, offshore plants, or wind-power plants [7].
However, SF₆ was labeled as one of the greenhouse gases in the Kyoto Protocol and Paris Agreements owing to its excessive size, radiative effect, and atmospheric lifetime [8–12]. The global warming potential (GWP) of SF₆ is 23,500 times that of carbon dioxide (CO₂) over a 100-year time horizon and is 32,600 times that of CO₂ over a 500-year time horizon. The atmospheric lifetime of SF₆ is 3200 years, whereas that of CO₂ is only 30–90 years [1]. It was reported that 1 kg of SF₆ released into the atmosphere has the equivalent global warming impact as 23.5 tons of CO₂ [13]. Therefore, emission and consumption of SF₆ must be controlled by the year 2020 and regulations have been implemented to reduce the environmental impact caused by SF₆ [14–16]. In addition, SF₆ decomposes into lower fluorides of sulfur when an electrical discharge such as an arc, spark, or corona occurs. Some decomposition byproducts, including disulfur decafluoride (S₂F₁₀), sulfur tetrafluoride (SF₄), and hydrogen fluoride (HF), are known to be highly reactive, corrosive, and toxic, which cause great concerns regarding equipment lifetime and personnel safety [17,18].

Negative impacts have led the power industry to seek an eco-friendly alternative insulation gas to partially or completely replace SF₆. Studies have been carried out to investigate the potential of natural gases such as CO₂ [19] and nitrogen (N₂) [20], and dry air, vacuum, SF₆ gas mixture [20–22], and fluorinated gases with reduced GWP such as trifluoriodomethane (CF₃I) [4,15,14,23,24], perfluorocarbons (PFCs) [1,25], as well as hydrofluoroolefins (HFOs) [7,26]. Unfortunately, all of them have respective drawbacks, making them unsuitable for application in high-voltage gas-insulated equipment.

Recently, green gas for grid (g₃), which was developed in collaboration by General Electric and 3M Company, has been regarded as the latest generation insulation gas and is the most promising candidate for replacing SF₆. G3 is a gas mixture that is composed of C₄F₇N (Novec™ 4710) and CO₂ or N₂, which aims to reduce the environmental impact and to find a compromise between the dielectric performance and the minimum operating temperature of the apparatus [26–28]. Properties of g₃ gas have been individually studied in the past five years, whereas a comprehensive overview of g₃ gas for applications in high-voltage gas-insulated equipment has not been presented until now. This paper firstly discusses the required physical and chemical properties of gas for high-voltage insulation applications and then carries out a review on the state-of-the-art performance investigations of g₃ gas.

2. Required Physical and Chemical Properties of Insulation Gas

An environmentally sustainable insulation gas alternative to SF₆ should be compliant with the stringent requirements of high-voltage applications [29,30]. The physical and chemical properties include

- High-dielectric strength;
- Good arc-quenching capability;
- High heat dissipation (high thermal conductivity);
- Low boiling point and high vapor pressure at low temperature;
- Compatibility with other materials; and
- Design compactness.

In addition, it also has to meet environmental and safety requirements, such as

- Low GWP;
- No ozone depletion potential (ODP);
- Low toxicity; and
- Nonflammable and nonexplosive.
2.1. Dielectric Strength

The dielectric strength is investigated by AC, DC, and lightning impulse breakdown voltage, which is performed in the electrode arrangement and practical gas-insulated power facilities. Breakdown mechanisms of insulation gases can be theoretically explained by Paschen’s law and the Townsend theory [31,32]. The AC and DC breakdown voltages are tested by raising the applied voltage at a constant rate until the breakdown occurs. The lightning impulse breakdown voltage, which is represented by 50% breakdown strength, is determined by the up-and-down method by applying a 1.2/50 s standard lightning pulse voltage. Since it is used for determining the basic insulation level of a system, the lightning impulse test is a crucial test. The breakdown test, under the same condition, is repeated multiple times so that the mean value and standard deviation of the breakdown voltage are calculated by evaluating the gas performance [28,33]. Various conditions should be taken into account for determining the breakdown voltage, including the homogenous and inhomogeneous field, surface roughness, insulation defects, free-moving conductive particles, and contamination [34–37].

In addition to the breakdown voltage, partial discharge (PD) is the other criterion for evaluating the dielectric strength. According to the International Electrotechnical Commission (IEC) 60270, PD is a localized electrical discharge that only partially bridges the insulation between conductors, and it can or cannot occur adjacent to a conductor [38]. It occurs at any point in the insulation system where the electric field strength exceeds the breakdown strength of gas. Therefore, PD is regarded as an early stage of breakdown [39–41]. PD characteristics, in terms of partial discharge inception voltage (PDIV), discharge magnitude, and pulse count as a function of gas pressure and insulation distance, are used to compare the insulation performance of alternative gases [42–44].

2.2. Arc-Quenching Capability

Insulation gases should have the ability to interrupt a large current during the switching operation of the circuit breaker [45,46]. Important gas properties for arc interruption are required. The insulation gas should be electronegative to capture the freed electron fast and to reduce its moving speed [47]. As arc temperature is more than 10,000 K; gases should have high thermal conductivity to quickly cool down the temperature. In addition, molecules may be dissociated at a high temperature. The fast dielectric recovery is, therefore, required to recombine gas to form its original structure [36]. The arc-interrupting ability is evaluated by the thermal-interrupting test and the dielectric-recovery test. The arc conductivity, at hundreds of nanoseconds before current zero, is used as a performance indicator of the thermal-interrupting test [48,49]. The dielectric recovery test is currently done by a computational fluid dynamic of gas flow [50].

2.3. High Heat Dissipation (High Thermal Conductivity)

High heat dissipation capability is not only required to ensure arc-quenching ability but is also essential to transmit heat from the conductor and contact that is caused by the large current [51,52]. It is specified in the IEC 62271 that the highest temperature of the busbar and enclosure must not exceed 105 °C and 70 °C, respectively. The maximum allowable temperature rise during the steady-state operation of the busbar must not exceed 65 K, and that of the enclosure is 30 K [53]. Heat-dissipation performance of alternative gases can be determined by temperature rise testing in actual operation and simulated calculation, such as the analytical method and the finite element method [30,51,52,54].

2.4. Boiling Point and High Vapor Pressure at Low Temperature

In the Institute of Electrical and Electronics Engineers (IEEE) C37.100.1 standard, the minimum ambient operating temperature required for the outdoor switchgear is −30 °C [55]. The most frequent minimum temperatures requested by the main users of electrical switchgear are −15 °C and −25 °C [56]. To avoid liquefaction and to ensure the medium remains gaseous within the operational temperature range of the power apparatus, alternative gas should have a low boiling point and high vapor pressure...
at low temperatures [7,57]. Correlation between saturated vapor pressure and temperature data of gas mixtures can be obtained by the Wagner equation, which is given by

$$\ln \left( \frac{p}{p_c} \right) = (aτ + bτ^{1.5} + cτ^3 + dτ^6) \frac{T}{T_c}$$

(1)

where $p$ and $p_c$ are the partial pressure and critical pressure of gas mixtures, and $T$ and $T_c$ are the thermodynamic temperature and critical temperature, respectively [27,58].

2.5. Compatibility with Other Materials

Alternative insulation gases are not chemically as inert as SF₆ and might react with other substances such as metals, spacers, insulators, etc. As a result, the serviceable lifetime of power facilities may be significantly diminished. Therefore, intensive investigations about material compatibility between the new gas as well as its decomposition and the other used materials are required, which can be done in long-term aging tests at increased temperatures [59].

2.6. Design Compactness

The most desirable alternative gas is the substitute that can be used in existing SF₆-insulated facilities without significant changes in structure, operation, and ratings [36]. In addition, power facilities designed with an alternative gas should have a similar footprint to SF₆ units and avoid an increase in space.

2.7. Global Warming Potential

According to the Intergovernmental Panel on Climate Change (IPCC), the GWP is defined as an index of the climate impact added to the climate system by a greenhouse gas relative to that added by CO₂ [60]. It is calculated as the ratio of the time-integrated radiative forcing due to 1 kg of the gas emitted to the atmosphere relative to that of 1 kg of CO₂ over an integration time horizon (ITH), which can be expressed by

$$\text{GWP} = \frac{\int_0^{\text{ITH}} R_x C_x \exp\left[-\frac{(t - t_0)}{\tau_x}\right] dt}{\int_0^{\text{ITH}} R_{CO_2} C_{CO_2}(t) dt}$$

(2)

where $R$ and $C$ are the radiative forcing per unit mass and the atmospheric concentration of the compound, respectively; $t$ and $t_0$ are the time and compound of interest; and $\tau$ is the lifetime of compound [61]. Commonly, ITH of 20, 100, and 500 years are used.

The GWP of a gas mixture is calculated as a weighted average, derived from the sum of the weight fractions of the individual gas multiplied by their GWP [62,63].

$$\text{GWP}_{\text{mixture}} = \sum [(\text{Gas} X\% \times \text{GWP}) + (\text{Gas} Y\% \times \text{GWP}) + \cdots + (\text{Gas} N\% \times \text{GWP})]$$

(3)

where % is the contribution by weight with a weight tolerance of 1%.

2.8. Ozone Depletion Potential (ODP)

As the environmental impact of SF₆ is the main reason to search for a substitutable gas, any alternative gas must not increase the environmental concerns and have an ozone depletion potential of zero.

2.9. Toxicity

Any alternative gas and its byproducts should have minimal toxicity to ensure that it can be safely handled as it is procured, transported, maintained, and disposed of, and that it is not harmful when the gas is released to the atmosphere. Important indicators of toxicity are acute toxicity, chronic...
toxicity, as well as medium- and long-term toxic effects [56]. Acute toxicity is characterized by a lethal concentration at 50% mortality (LC50) in 4 h. LC50 is expressed in parts per million (ppm), and a low value corresponds to high-gas toxicity. The acute toxicity of a gas mixture is determined by the calculation of the toxicity for all relevant ingredients [64]. Chronic toxicity is presented by the time-weighted average (TWA) and measured in ppm in 8 h. The TWA should be higher than 50 ppm in the switchgear factories to ensure workers continue without adverse effects. Medium- and long-term toxic effects are carcinogenic, mutagenic, and toxic for reproduction [56,59].

3. Green Gas for Grid

Although Novec™ 4710 has excellent dielectric strength and an arc-quenching ability, it cannot be used alone due to its high-liquefaction temperature. Therefore, it is necessary to mix it with other gases such as CO2 and N2. Addictive Novec™ 4710 in gas mixtures is in the range of 5–20% [26,27]. Table 1 shows the fundamental physical and chemical properties of SF6, Novec™ 4710, CO2, and N2.

Table 1. Fundamental physical and chemical properties [20,25,65].

| Chemical Formula | SF6 | CF3N | CO2 | N2 |
|------------------|-----|------|-----|----|
| Molecular weight (g/mol) | 146.06 | 195 | 44.01 | 28.014 |
| Number of electrons | 77 | 48 | 16 | 7 |
| Relative dielectric strength to SF6 | 1 | >2 | <0.4 | <0.4 |
| Liquefaction pressure at −30 °C (MPa) | 0.52 | 0.0311 | 1.43 | - |
| Freezing point (°C) | −51 | −118 | −78.5 | −210 |
| Boiling point at 0.1 Mpa (°C) | −63 | −4.7 | −79 | −196 |
| Ozone depletion potential | 0 | 0 | 0 | 0 |
| Global warming potential (GWP) | 23,500 | 2100 | 1 | 0 |
| Atmospheric lifetime (year) | 3200 | 30 | 5–200 | - |
| Toxicity (LC 50 (rat)) | >500,000 | 10,000–15,000 | >300,000 | - |
| Flammability | No | No | No | No |
| Corrosion | No | No | No | No |

The dielectric strength of g3 gas has been investigated by breakdown voltage and PD. Figure 1 shows the AC breakdown voltage depending on the Novec™ 4710 and CO2 mixture ratio, as well as the gas pressure in the uniform field that was configured using parallel disk electrodes with a gap distance of 2.54 mm [66]. The AC breakdown voltage was also measured on a 145 kV GIS with Novec™ 4710 ratio from 0% to 20% and CO2. It was indicated that the dielectric strength of pure CO2 was equivalent to about 40% that of SF6 at atmosphere pressure. Adding 6% to 7% of Novec™ 4710 doubled the dielectric strength, and g3 gas with 18% to 20% of Novec™ 4710 had the equivalent dielectric strength to SF6 at atmosphere pressure [30,67,68]. Breakdown tests under AC at different pressures and electrode distances were conducted in plane–plane, sphere–plane, rod–plane, and needle–plane electrode configurations. In the uniform field, equivalent dielectric strength to SF6 at 100 kPa can be reached by a mixture containing 15% Novec™ 4710. In the nonuniform and highly nonuniform fields, SF6 exhibited higher dielectric strength than a 20% mixture. The 20% Novec™ 4710/80% CO2 mixture at 100–120 kPa was verified as an optimal potential replacement of SF6 as the dielectric medium in MV switchgears if attention is paid to the equipment design to avoid nonuniform fields [44]. The comparison of AC breakdown voltages in the sphere-to-sphere electrode arrangement showed that the 3.7% Novec™ 4710/96.3% CO2 mixture constituted a good compromise between high-voltage apparatus insulation and a low ambient temperature application [28].
The positive and negative DC breakdown tests were carried out in a plane–plane electrode arrangement. As shown in Figure 2, the negative DC breakdown strengths of 4% Novec™ 4710/96% CO₂ and 8% Novec™ 4710/92% CO₂ mixtures at 0.7 MPa were 81.21% and 96.48% of the value for SF₆ at 0.5 MPa [57,69]. The lightning breakdown voltages of 3.7% Novec™ 4710/96.3% CO₂ at pressures of 0.88 MPa and 1.04 MPa were almost equivalent to that of SF₆ at 0.55 MPa and 0.65 MPa, respectively [28].

PDIVs of SF₆ and Novec™ 4710/CO₂ were measured in protrusions on the conductor and enclosure of GIS. As shown in Figure 3, PDIVs in g₃ gas with 4% Novec™ 4710/96% CO₂ in protrusion defects were measured as 76–84% of that of SF₆. In addition, the average apparent charge and pulse count of PD in g₃ were higher compared with those in SF₆ [70]. The PDIV in Novec™ 4710/N₂ showed that the dielectric strength of the gas mixture was weaker than that of pure SF₆ [27].

**Figure 1.** AC breakdown voltage depending mixture ratio and gas pressure [66].

**Figure 2.** DC breakdown strength of the Novec™ 4710/carbon dioxide (CO₂) mixture depending on gas ratio and pressure [57].

**Figure 3.** PDI (kV/mm) of SF₆ and Novec™ 4710/CO₂ in protrusions on GIS [70].
The switching bus-transfer current test was carried out on a 420 kV disconnector over a 100 close and open operation under 1600 A and 20 V. Comparison of the arcing time between Novec\textsuperscript{TM} 4710/CO\textsubscript{2} gas mixture and SF\textsubscript{6} is shown in Figure 4. It indicates that the arcing time of g3 gas proved to be stable, and the average arcing time is about 12 ms, compared with a typical value of 15 ms for SF\textsubscript{6} [67]. The arc-quenching capability was verified according to IEC 62271-100, also indicating that g3 gas maintained the appropriate dielectric withstanding ability after repeated interruptions [68,71,72].

Temperature rise tests of g3 gas were performed on a fully equipped three-phase GIS bay, and the results are shown in Figure 5. There were temperature rise differences of 5 K to 6 K between the gas mixtures and SF\textsubscript{6} [26,67]. The temperature rise can be compensated for by typical measures such as adding cooling fins to the enclosure or machining slots and holes to conductors to improve convection around live parts of the GIS.

**Figure 3.** Partial discharge inception voltages of SF\textsubscript{6} and g3 in the protrusion defects [70].

**Figure 4.** Arcing time of Novec\textsuperscript{TM} 4710/CO\textsubscript{2} gas mixture and SF\textsubscript{6} [26].

**Figure 5.** Temperature rise of g3 gas mixtures compared to SF\textsubscript{6}.
Novec™ 4710 has a liquefaction temperature of −4.7 °C at 0.1 MPa, which makes it impossible to be applied in gas-insulated power facilities alone. N₂ or CO₂ is used as a buffer gas to increase the liquefaction temperature. The liquefaction temperature of Novec™ 4710/N₂ and Novec™ 4710/CO₂ gas mixture at different gas ratios and pressures can be calculated according to Equation (1). The results are illustrated in Figure 6. To meet the minimum ambient operating temperature requirement of −30 °C, NOVEC™ 4710 should be at least at 13% at 0.2 Mpa in the Novec™ 4710/N₂ and Novec™ 4710/CO₂ mixture.

Materials of the gas-insulated structure have been found to be compatible with the Novec™ 4710. There is no research so far indicating the chemical reaction of Novec™ 4710 with other materials.

According to Equation (3), the GWP of g3 gas mixed with CO₂ or N₂ can be calculated according to the Intergovernmental Panel on Climate Change and the Regulation No 842/2006 of the European Parliament and the Council of 17 May 2006 on Certain Fluorinated Greenhouse Gases [62,63]. Figure 7 shows the GWP of the g3 gas mixture with Novec™ 4710 ratio up to 20%. The GWPs of 20% Novec™
4710/80% CO₂ and Novec™ 4710/80% N₂ are 1104 and 1334, which are only 4.7% and 5.7% that of SF₆, respectively. Therefore, the application of g3 gas results in a significant reduction in GWP.

In addition, g3 gas has an ODP of zero, and its atmospheric lifetime is much shorter than that of SF₆. g3 is not a carcinogenic and mutagenic gas, and is classified as nontoxic, nonflammable, and nonexplosive [61,70].

g3 gas has been verified as an effective and high-performance substitute of SF₆ for environmentally sustainable high-voltage applications. At present, g3 gas-insulated power facilities are commercially available for GIS up to 145 kV, GIL and GCB up to 420 kV, and GIT up to 245 kV, after stringent laboratory and equipment testing [30]. These facilities feature the same dimensional footprint as SF₆ equipment, while significantly reducing greenhouse gas emissions.

4. Conclusions

As a new potential alternative insulation gas to SF₆, g3 that is composed of Novec™ 4710 and CO₂ or N₂ shows its high performance as an insulation medium of gas-insulated power facilities. This paper presents a comprehensive overview of g3 gas for applications in high-voltage, gas-insulated equipment, and conclusions are as follows:

1. From the AC/DC breakdown voltage and partial discharge characteristics, the addition of a few ratios of Novec™ 4710 to the buffer gas significantly increases the dielectric strength of the gas mixture, which is almost equivalent to that of SF₆.
2. At the same time, g3 presents a good compromise between high dielectric strength and low ambient temperature requirements, which met the requirement of the minimum ambient operating temperature of power facilities.
3. In addition, the switching bus-transfer current test, temperature rise test, and liquefaction temperature calculation also verified the validity of g3 gas for high-voltage insulation applications.
4. As for environmental concerns, g3 gas reduces the GWP of more than 94% compared with SF₆. It has an ODP of zero and an atmospheric lifetime as short as 30 years, which is only 1% of that of SF₆.

From the laboratory and equipment testing, g3 is verified as the most promising eco-friendly alternative insulation gas to SF₆ developed for the SF₆-free gas-insulated power facilities. It is a potential alternative for electrical equipment with a drastically reduced environmental impact while featuring the same structure, operation, ratings, and footprint of existing equipment.
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