International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 13, No. 2, June 2022, pp. 1101~1110
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v13.i2.pp1101-1110

Modelling G^3 gas as an alternative gas for SF_6 using COMSOL multiphysics

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Article Info

Article history:

Received Dec 15, 2021
Revised Apr 21, 2022
Accepted May 7, 2022

Keywords:

(A-HeptaFluoro-iso-Butyronitrile+CO_2) G^3 gas
COMSOL multiphysics
Gas insulated switchgear
Sulfur hexafluoride SF_6 gas

ABSTRACT

Sulfur hexafluoride (SF_6) gas is the most often gas used in high voltage systems as insulating medium and arc quenching because it has many advantages such as high dielectric strength, low boiling point, low toxicity, and stability for a long period. The 1997 Kyoto protocol recommended the elimination of SF_6 gas, because its impact on the atmosphere has global warming potential (GWP) equal to 23,500 and an ozone depletion potential (ODP) equal to 0.08. Kyoto protocol recommended alternatives gases for SF_6 gas such as CF_3CHCL_2, and others. In this paper a new gas called a HeptaFluoro-iso-Butyronitrile+CO_2 ([$(CF_3)2CFCN+CO_2$]) which is known commercially as green global gas (G^3) The dielectric strength for the proposed gas is approximately equal to SF_6 gas and excellent arc quenching and achieve Kyoto protocol recommendations about using alternative gases with 98% less impact on GWP than SF_6 gas also G^3 gas maintain the same dimension and overall footprint which is an important economical factor for utilities. The total bond energy analysis of SF_6 and G^3 gases has been studied. COMSOL multiphysics was used to simulate the SF_6 and G^3 gases to show the ability of the G^3 gas when working in geographic information system (GIS) equipment.

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1. INTRODUCTION

The modern transmission and distribution equipment's working in medium and high voltage relies on sulfur hexafluoride (SF_6) gas as insulating and arc quenching because this gas achieves all requirements needed for this purpose such as high dielectric strength, good arc quenching, low boiling point, heat dissipation, design compartments, and stability for a long time inside the equipment [1]. In 1997 Kyoto protocol recommended reducing the SF_6 gas because of the high effect on the atmosphere in which the global warming potential (GWP) is 23,500. Ozone depletion potential (ODP) equal to 0.08. Table 1 shows the gases recommended Kyoto protocol which is included in the family of hydro chlorofluorocarbon (HCFC) gas [2]–[6]. The proposed gas achieves all Kyoto protocol recommendations and high voltage switchgear specifications such as high dielectric strength, good arc quenching capability, low boiling point, high vapor pressure at low temperature, and high heat dissipation compatibility with switchgear material [1], [7].

For more than ten years two companies work in the field of gases generate new gas as the chemical compound a HeptaFluoro-iso-Butyronitrile+CO_2 ([$(CF_3)2CFCN+CO_2$]) which is commercially known as green global gas (G^3) [9]. This new gas is consist of two main compound one called (Novec 4710) with

(4$_{mol}$% to 6$_{mol}$%)+CO_2 with (96% to 94%) respectively [9], [10]. The comparison between the main component of G^3 (Novec 4710) and SF_6 gas is stated in Table 2.

Table 1. The Kyoto protocol gases recommendation [8]

Chemical name	chemical formula
Dichlorofluoromethane	$CHCl_2F$
Chlorodifluoromethane	$CHClF_2$
Dichloromethane	CH_2Cl_2
Chlorofluoromethane	CH_2ClF
Tetrachlorofluoroethane	C_2HFCl_4
Trichlorofluoromethane	$C_2HF_2Cl_3$
Dichloro-trifluoroethane	$CHCl_2CF_3$
2-chloro-1,1,1,2-tetrafluoroethane	$CHClFCF_3$
Trichlorofluoromethane	$C_2H_2FCl_3$
Dichlorodifluoroethane	$C_2H_2F_2Cl_2$
Chlorotrifluoroethane	$C_2H_2F_3Cl$
1-chloro-1-fluoroethane	CH_3CCl_2F
Chlorofluoroethane	C_2H_4FCl
Hexachlorofluoropropane	C_3HFCl_6
Pentachlorodifluoropropane	$C_3HF_2Cl_5$
Tetrachlorotrifluoropropane	$C_3HF_3Cl_4$

Table 2. Comparision between Novec 4710 and SF_6 [11]

Gas properties at 25 ℃	Novec 4710 gas	SF_6 gas
Molecular weight (g/mol)	195	146
Flash point (℃)	Nonflammable	Nonflammable
Freezing point (℃)	-118	-51
Boiling point (℃)	-5	-64
Vapor pressure (KPa)	297	2149
Gas Density at 1 bar (kg/m^3)	7.9	5.9
Dielectric strength at 1 bar (kV over 2.5 mm gap)	27.5	14
Atmospheric lifetime (years)	30	3200
Ozone depletion potential (ODP)	0.00	0.08
Global warming potential (GWP)	2100	23500

From Table 2 the dielectric strength of Novec 4710 is 1.96 more than SF_6 gas so when added to CO_2 gas to generate the proposed G^3 will achieve the main properties to be alternative gas in geographic information system (GIS). Also, the GWP for Novec 4710 when 1 kG leaks to the atmosphere equal to 2,100 kG from CO_2 gas where every 1 kG leak from SF_6 gas to atmosphere equal to 23,500 kG from CO_2 gas as shown in Figure 1. The ODP for G^3 gas is equal to zero but for SF_6 gas equal to 0.08 which means that using the proposed gas could lead to more enhancement for ODP [12]. From 1994 to 2016 as shown in Figure 2 the concentration of SF_6 gas in the atmosphere where shown that during the last five years the concentration of SF_6 gas was increased by 20% [13], [14]. So, the potential alternative gas should be worked in all industrial works to reduce the main effect of this gas (greenhouse effect) which is one of the important recommendations of the Kyoto protocol that needed to be achieved [15].

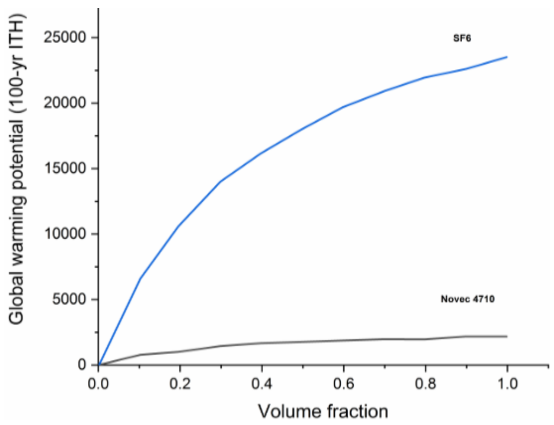


Figure 1. GWP values for SF_6 gas and G^3 gas [11]

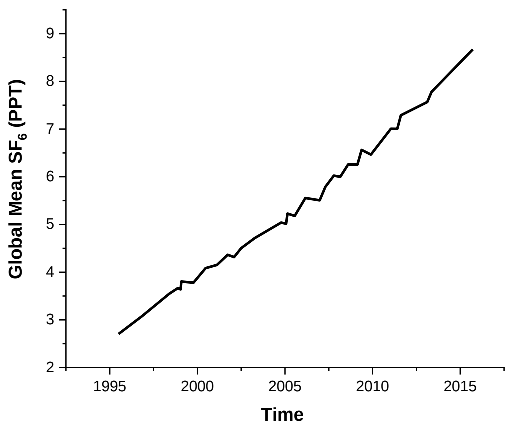


Figure 1. SF_6 gas concentration in the atmosphere [13]

2. [$(CF_3)_2CFCN+CO_2$] G^3 CHARACTERISTICS

2.1. Mixtures with CO_2 gas

When using CO_2 gas with Novec 4710 and not using N_2 gas or dry air because of the superior arc quenching capability for CO_2 gas. Novec 4710+CO_2 gas called G^3 gas which used with two approved ratios. The first one is 4_{mol}% Novec 4710+96% CO_2 and the second ratio is 6_{mol}% Novec 4710+94% CO_2. These two ratios are the famous which used as alternative gas for SF_6 gas [16], [17]. From Figure 3 when the fluoronitrile content reaches 18-20% in the new gas a pressure equal to1 bar then the dielectric strength will be equal to SF_6 gas [11].

2.2. Toxicity of G^3 gas

According to OECD 403, the acute toxicity level of the arced gas was recovered from the arcing test was determined through LC_{50} on females and males of mice. The experimental that were done at the University of Montpellier, France indicate that ten animals were exposed to arced G^3 gas for four hours and these mice were observed for 14 days after exposure to detect the molarity rate. The LC_{50}_4H that the female mice were 64,000 ppm and 66,000 ppm for males. This mean that the concentrations are three-time above the toxicity class. The higher the LC_{50} indicate the lower the toxicity level. There is a sufficient margin of worker safety that should be achievable under release scenarios [10]. Figure 4 shows the main components that can be adsorbed when G^3 gas be arced for circuit breaker operating in the field [18]. These adsorbents were not present during the arc interruption tests so they would not influence and reduce the by-product composition and toxicity of the gas.

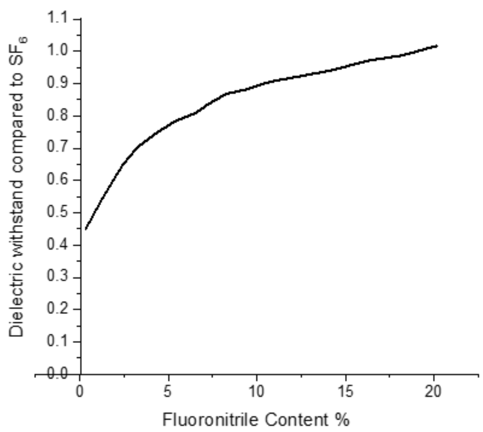


Figure 3. Dielectric strength for G^3 gas compared with SF_6 gas [11]

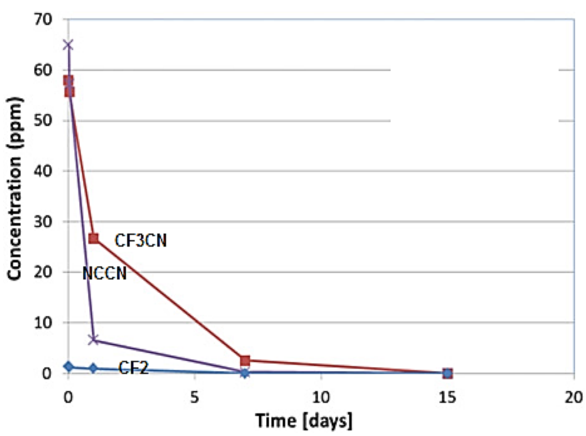


Figure 4. G^3 arced gas by-products adsorption rate [18]

2.3. G^3 Gas physical characteristics

It's known that CO_2 gas and Novec 4710 follow the Van der Waals equation where the temperature dependence of the total pressure of the proposed gas can be derived from the sum of both partial pressures plus the homogeneity of the gas was studied proving that no special mechanism required to achieve the G^3 gas when comparing with any mixture such as SF_6+CO_2, SF_6+N_2 [19]. The proposed gas is still homogeneous for a long time even if the temperature lowers than the minimum point. For G^3 gas many experiments were done to show that the fluorinated gases with low vapor pressure but high dielectric strength as shown in Figure 5. So Novec 4710 can't work alone as insulated gas and arc quenched but after mixing with CO_2 gas to reach to acceptable liquefied temperature. The preferable ratio is 4_{mol}% to 6_{mol}% from (Novec 4710) plus 94% to 96 % from CO_2 [20].

2.4. The G^3 gas heat transfer performance

The G^3 gas has the potential to replace the SF_6 gas due to the characteristics mentioned in Table 2. But the heat transfer performance should be studied for this proposed gas to be verified. From an experiment that was done in the heat transfer performance of the new mixture G^3 gas increased with increasing the mole concentration of Novec 4710 which CO_2 increase the temperature of the surrounding of the gas insulated line (GIL) [22].

The maximum temperature rise for GIL is 39.8 K when using the SF_6 gas under 0.5 Mpa but when using the G_3 gas the temperature is 42 to 45 K for 4_{mol}% Novec 4710 and 8_{mol}% Novec 4710 respectively as shown in Figure 6 [19]. Also from Figure 6, the pressure at 0.7 Mpa the temperature of the conductor surface will increase by 5.8 to 2.5 K when using 4_{mol}% Novec 4710 and 8_{mol}% Novec 4710 respectively. So these temperature increases agree with an acceptable level of heat transfer for GIL.

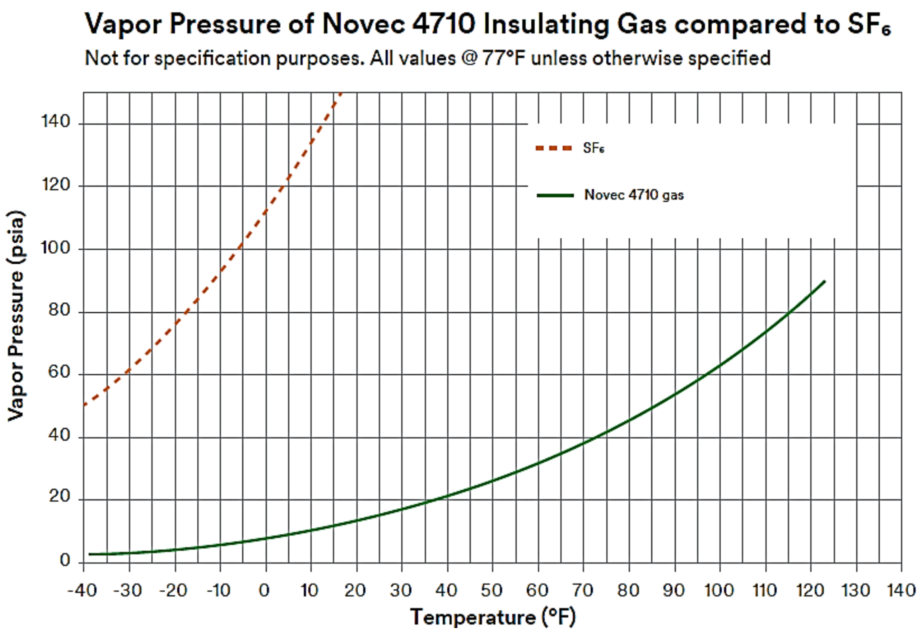


Figure 5. Vapor pressure of Novec 4710 insulating gas compared to SF_6 [21]

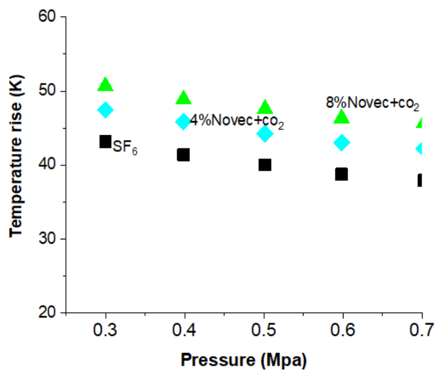


Figure 6. SF_6 gas and two Novec 4710/CO_2 mixture at different pressure [19]

2.5. G^3 gas first application

Gas insulated line GIL energized by 420 kV for the first application that the proposed gas. The mass of G^3 gas brings a quick and massive reduction by 50% from SF_6 gas. In the United Arab Emirates there is GIL with 13 km length and 420 kV in Jebel Ali station. Where SF_6 gas mass was 73 tons which is equivalent to 1700 tons from CO_2 gas. Impact of gas losses over 40 years (CO_2 gas) reduced to 98% when using G^3 gas [23]. Table 3 shows the benefits of using the G^3 gas from different parameters such as mass, quantity, joule losses, and impact of gas losses [23].

Table 3. G^3 gas and SF_6 gas in Jebel Ali station GIL

Specifications	T155 420 kV SF_6 gas	T155 420 kV G^3 gas	%
The total mass of the GIL (kg)	12.046	12.995	7.9
Gas quantity in kg	1649	743	-55
Joule losses over 40 years	1242	1169	-5.9
Impact of gas losses over 40 years (eq.CO_2 gas)	7749	102	-98.7

3. MODELING SF_6 GAS AND G^3 GAS BY COMSOL MULTIPHYSICS

Using the SF_6 gas and G^3 gas as an insulating medium for three phase busbar with 100 kV energized voltage to show specific characteristics of the two gases such as electric potential, arc length, and electric field norm V/m. The main geometry is constructed in COMSOL multiphysics as three busbars in a compartment that takes a circular shape. The main compartment has a radius of 25 cm, for the busbars take the radius of 5 cm as shown in Figure 7.

3.1. Modeling the SF_6 gas and G^3 gas

The main geometry was shown in Figure 7. Also, the materials for busbar from copper, and gas SF_6 and G^3 specifications used in this simulation were stated in Table 4. The main body of the vessel made from aluminum. Also, there are two types of vessels, one of them contain one phase with more current and extra voltage with good insulation, the second one as used in our paper has three phase with low current, high voltage, and good insulation.

Table 4. Material properties for SF_6 gas and G^3 gas

Material	Domain	Relative Permittivity	Electrical conductivity (S/m)
Copper	2-3-4	1 [24]	5.813e7
SF_6 gas	1	1 [25]	1e-10 [26]
G^3 Gas	1	0.88 [7]	1e-8 [26]

3.1.1. The boundary conditions

The three busbars are supported by spacers who work as insulators. The spacers should have more specification in further studies where the insulation for the compartment depends on it. The spacers in general made from epoxy and for enhancement the insulation nanotechnology was used to better support and overcome the partial discharge problems. The busbar was energized by 100 kV and the main compartment were grounded.

3.1.2. Meshing

After specifying the boundary condition and inserting copper, SF_6 gas, and G^3 gas properties then meshing is performed on the circular compartment. The meshing type was a physically controlled one and the element size is extremely fine to reach accurate results as shown in Figure 8. Meshing will define potential at nodes of every finite element where the potential value is used to get electric field value at that point.

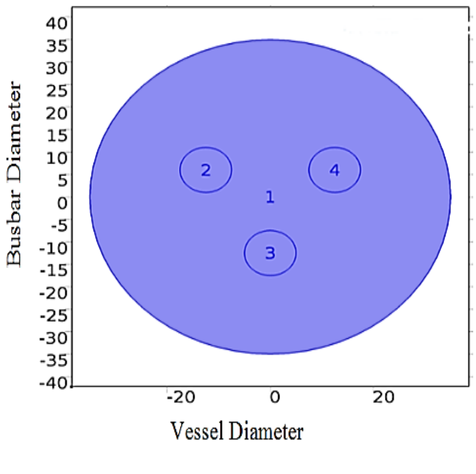


Figure 7. The structure of the bus bar and main compartment

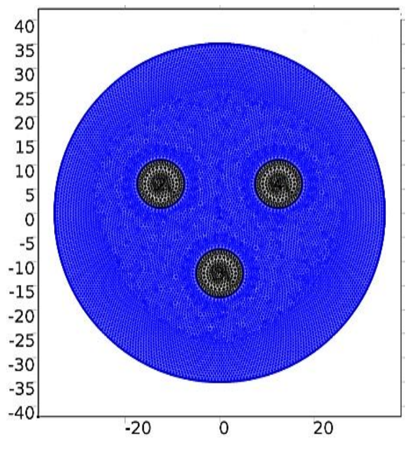
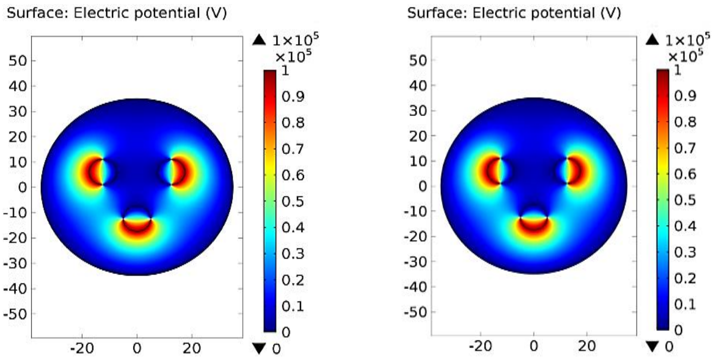


Figure 8. Meshing the structure for SF_6 gas and G^3 gas

3.1.3. Simulation results

The first phenomenon is electric potential in all the structure as shown in Figure 9(a) for SF_6 gas and Figure 9(b) for G^3 gas which indicates aseparate distance without any potential between the busbar. This result indicatesthat the two gases withstand the electric potential without any problems. For demonstrating the electric field norm and electric field potential an imaginary line was drawn between the two busbars as shown in Figure 10.



(a) (b)

Figure 9. Electric potential (V) for SF_6 gas (a) and G^3 gas (b) as an insulating medium

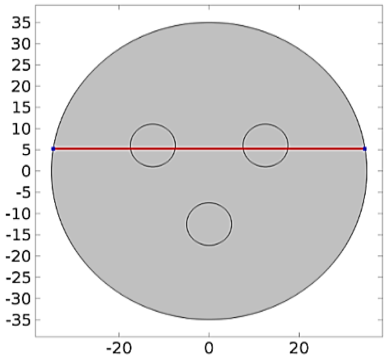
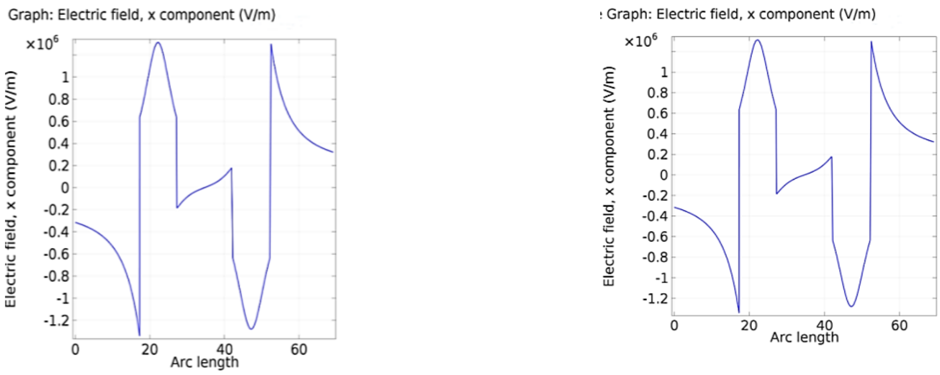


Figure 10. Imaginary line between two busbars

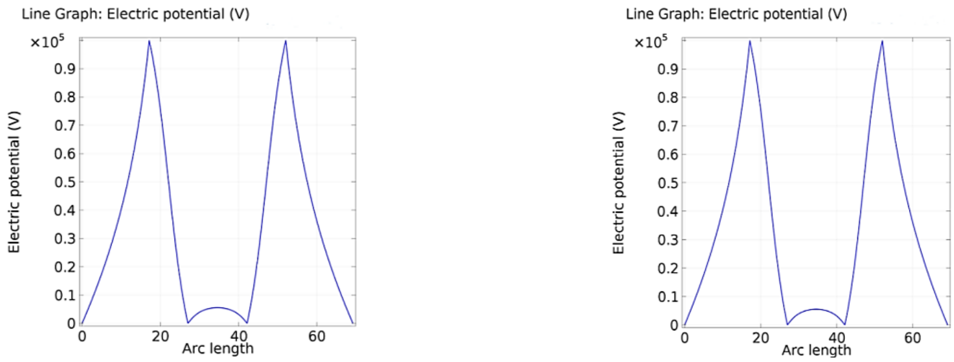
The second phenomenon is the electric field vs arc length where is shown in Figures 11(a), (b) for SF_6 and G^3 respectively it was observed that when using SF_6 gas electric field magnitude is reached to the max 1.341906×10^6 V/m and min -1.369534×10^6 V/m and when using G^3 gas electric field magnitude is reached to the max $1.369534\text{x}10^6$ V/m and min $-1.369534\text{x}10^6$. Which meaning the two gases are approximately equal in electric field vs arc length.

Another phenomenon is called electric potential vs arc length which indicates that the insulation of electric field max 100.989×10^5 V and min -987 V for SF_6 gas as shown in Figure 12(a) and for G^3 gas the insulation of electric field max 100.986×10^5 V and min -986 Vas shown in Figure 12(b) for the G^3 gas when drawing an imaginable line between two conductors to measure the electric field.



(a) (b)

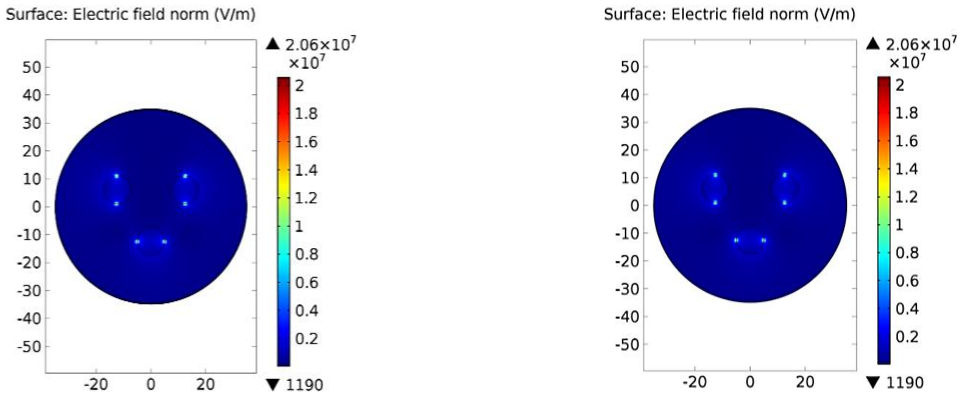
Figure 2. Electric field and arc length for (a) SF_6 gas and (b) G^3 gas



(a) (b)

Figure 3. Electric potential with arc length for (a) SF_6 gas and (b) G^3 gas

The last phenomenon is the concentration of the electric field behind the spacers (ground) which indicates the maximum value is 2.06×107 V and the minimum value is 1190 V for SF_6 gas and G^3 gas as shown in Figures 13(a) and 13(b).



(a) (b)

Figure 4. Electric field concentration behind the spacers for (a) SF_6 gas and (b) G^3 gas

4. RESULT AND ANALYSIS

4.1. From Kyoto protocol recommending

SF_6 gas should be eliminated to reduce the effects on GWP and ODP, and others. Using G^3 gas achieves all requirements from GWP, ODP, and low boiling point, high vapor pressure at low temperature, high heat dissipation, compatibility with switchgear material, and others. All these factors lead to know that G^3 gas is good alternative gas for SF_6 in high voltage equipment.

4.2. COMSOL multiphysics software results

Evaluation of the breakdown voltage of SF_6 and G^3 gases by using bond energy concept according to [26] the breakdown voltage for SF_6 and G^3 or any other gases can be calculated by knowing it's chemical structure and the value of atoms bond energy [27]. The results can be described in Table 5.

Table 5. Comparison of G^3 and SF_6 breakdown voltage

Gas		$U_b(eV)$	$V_b(kV)$	G^3/Sf_6 ratio
SF_6		20.34	89.8	
G^3	(a)	16.49	72.77	81 %
	(b)	17.98	79.3	88 %
	(c)	22.4	98.8	110 %
	(d)	20.55	90.7	100 %

– SF_6 gas

$U_b = 6(S-F)$ as shown in Figure 14. Where $(S-F)$ bond energy = 3.39 eV [27] and U_b is the total breakdown energy. Therefor:

$$U_b = 6 \times 3.39 = 20.34\ eV$$

And the breakdown voltage (V_b) equal to:

$$V_b = \frac{U_b}{Q_b} \qquad (1)$$

Where:
V_b is the total bond energy (eV) and Q_b is the total charge required at breakdown (arc) condition for gases, $Q_b = 226.6 \times 10^{-6}$ coulomb [26]. According to (1):

$$V_b = \frac{20.34}{226.6 \times 10^{-6}} = 89.8\ kV$$

– G^3 gas $[(CF_3)_2CFCN+CO_2]$ according to mixture ratio

– Novec 4710 [$(CF_3)_2CFCN$]

$U_b = 7(C-F) + 3(C-C) + (C \equiv N)$ as shown in Figure 15. Where $(C-F)$ bond energy = 4.6 eV, $(C-C)$ bond energy =3.6 eV and $(C \equiv N)$ bond energy = 9.23 eV. According to [26]:

$$U_b = 7 \times 4.6 + 3 \times 3.6 + 9.23 = 52.23 \text{ eV}$$

$$V_b = \frac{52.23}{226.6 \times 10^{-6}} = 230.5 \text{ kV}$$

– CO_2 gas

$U_b = 2(C = O)$ as shown in Figure 16. Where $(C = O)$ bond energy =7.5 eV. According to [26]:

$$U_b = 2 \times 7.5 = 15 \text{ eV}$$

$$V_b = \frac{15}{226.6 \times 10^{-6}} = 66 \text{ kV}$$

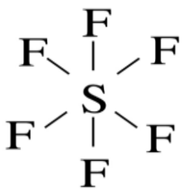


Figure 14. SF_6 structure

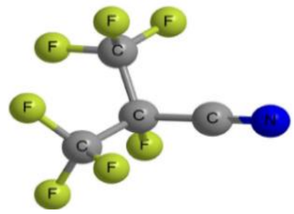


Figure 15. Novec 4710 structure

Figure 16. CO_2 structure

4.2.2. Breakdown voltage for SF_6 and G^3 (arc condition)

Firstly: SF_6 gas:

$$V_b = 90 \text{ kV}$$

Secondly: G^3 gas

a. Mixture ratio [4_{mol}% Novec 4710+96_{mol}% CO_2]

According to [26]

$$U_b(4_{mol}\%) = 0.04 \times 52.23 + 0.96 \times 15 = 16.49 \text{ eV}$$

$$V_b(4_{mol}\%) = \frac{16.49}{226.6 \times 10^{-6}} = 72.77 \text{ kV}$$

b. Mixture ratio [8_{mol}% Novec 4710+92_{mol}% CO_2]

$$U_b(8_{mol}\%) = 0.08 \times 52.23 + 0.92 \times 15 = 17.98 \text{ eV}$$

$$V_b(8_{mol}\%) = \frac{17.98}{226.6 \times 10^{-6}} = 79.3 \text{ Kv}$$

c. Mixture ratio [20_{mol}% Novec 4710+80_{mol}% CO_2]

$$U_b(20_{mol}\%) = 0.2 \times 52.23 + 0.8 \times 15 = 22.4 \text{ eV}$$

$$V_b(20_{mol}\%) = \frac{22.4}{226.6 \times 10^{-6}} = 98.8 \text{ kV}$$

d. Mixture ratio [15_{mol}% Novec 4710+85_{mol}% CO_2]

$$U_b(15_{mol}\%) = 0.15 \times 52.23 + 0.85 \times 15 = 20.55 \text{ eV}$$

$$V_b(15_{mol}\%) = \frac{20.55}{226.6\times10^{-6}} = 90.7\ kV$$

e. Novec 4710

The calculated results are in according with the results of COMSOL multiphysics for the equality of SF_6 and G^3 under case (d) [15_{mol}% Novec 4710 + 85_{mol}% CO_2]. But for 100% Novec the V_b= 230.5 kV and also these results agree with that given by [7], [12], [18].

$$U_b = 52.23 \text{ eV}$$

$$V_b = \frac{52.23}{226.6\times10^{-6}} = 230.5 \text{ kV}$$

5. CONCLUSION

SF_6 gas used in high voltage equipment as insulating and arc quenching for more than 40 years because it has high dielectric strength, good arc quenching capability, low boiling point, high vapor pressure at low temperature, high heat dissipation, and compatibility with switchgear material. But Kyoto protocol recommended that SF_6 gas should be eliminated because it has 23,500 GWP and 0.08 ODP. G^3 gas has approximately the same characteristics as SF_6 gas and at the same time have 2,100 GWP and zero ODP. The new proposed gas achieves all requirements from the Kyoto protocol and from required electrical specification. COMSOL multiphysics simulations prove that using G^3 ratio [15_{mol}% Novec 4710+85_{mol}% CO_2] and SF_6 for four cases are approximately equal in electric potential in all the structures, electric field vs arc length, electric potential vs arc length, and the concentration of the electric field behind the spacers (ground). The results of bond energy concept achieve the required breakdown voltage (arc condition) under all mixture cases and realize the accurate result comparison.

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