

Breakdown Voltage SF₆ Versus CF₃CHCl₂ Gas as Alternative for Gas Insulation Applied

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Abstract—Sulfur Hexafluoride Gas is a filling gas in Gas Insulated Switchgear equipment whose existence starts to be limited and reduced in accordance with amendments to the Kyoto Protocol. The utilization of new gas included in the list of recommendations for the Kyoto Protocol enters the implementation and application phases. Dichlorotrifluoroethane gas has equivalent capability even better than SF₆ gas so it is feasible to be recommended as a potential gas for SF₆ gas replacement. Experimental HV testing showed the gas capability to withstand breakdown voltage reaching 837 kV and had a techno-economic value 0.2 times cheaper than SF₆ gas. In the future CF₃CHCl₂ gas is very feasible and can be recommended as an environmentally friendly gas and is feasible as a potential alternative gas substitute for circuit breaker equipment in substation equipment that uses gas as a substitute for SF₆ gas.

Keyword - SF₆, Gas Insulated Switchgear, Protocol Kyoto, Techno-economic

I. INTRODUCTION

Discussing the power system cannot be separated from electrical material as an electrical equipment material or as an insulating media material on the electrical equipment used. Gas Insulated Switchgear (GIS) is electrical equipment that functions as a voltage separator in GIS equipment that uses gas media as an insulation medium and as an electric fire extinguishing medium due to the switching process [1]–[4]. Use of SF₆ (Sulfur Hexafluoride) gas as an insulator and fire arc extinguisher like a double-edged knife. On the function side, it is proven that SF₆ gas is very reliably used in GIS equipment because it has the ability to withstand 623 kV breakdown voltage and has the ability to extinguish electric arcs when moving quickly. The ability of SF₆ gas as a filler for GIS equipment is not offset by the environmentally friendly effects often voiced by environmental activists during this decade. SF₆ gas has S (sulfur) and F (Fluor) compounds in the formation of its chemical compounds. The results of the Kyoto Protocol identified that SF₆ gas was a gas that was not environmentally friendly and its used requires restrictions until the discovery of new gas as a substitute for SF₆ gas for GIS fillers [5]–[8].

SF₆ gas is the cause of the greenhouse effect and acid rain on the environment [9]–[11]. An active role is needed for researchers to be able to develop equipment and use of environmentally friendly materials as mandated in the Kyoto Protocol. Dichlorotrifluoroethane (CF₃CHCl₂) gas is one of the gases recommended by the Montreal Protocol and Kyoto Protocol as a potential gas alternative for SF₆ gas replacement which has the capability as a gas insulating material because of its ability to withstand greater breakdown stresses and the ability to extinguish the arc as gas has SF₆. CF₃CHCl₂ gas as a substitute for alternative gas for SF₆ gas has several conditions so that it can be applied to GIS equipment as an insulation medium and electric arc fire extinguisher.

Needed requirements:

1. Capability as insulation in resisting breakdown voltage.
2. The ability to extinguish electric arcs arising from the switching process.
3. Meet the requirements according to the Kyoto Protocol which includes Global warming potential, Ozone depleting Potential and atmosphere live-time.
4. Gas Has techno-economic value as a new material which is a potential substitute in terms of gas procurement costs.

Based on the Kyoto Protocol and the Montreal Protocol, the recommended gas can be seen in Table I. The gas which the Kyoto Protocol recommended is included in the family of HCFC (Hydrochlorofluorocarbon) gas [12]–[16]. The amount of research as active participation with the issuance of the Kyoto Protocol can be seen in research conducted by [17]–[20].

TABLE I. Gas Recommended Kyoto protocol

Chemical name	Chemical Formula
Dichlorofluoromethane	CHCl ₂ F
Chlorodifluoromethane	CHClF ₂
Dichloromethane	CH ₂ Cl ₂
Chlorofluoromethane	CH ₂ ClF
Tetrachlorofluoroethane	C ₂ HFCl ₄
Trichlorofluoromethane	C ₂ HF ₂ Cl ₃
Dichloro-trifluoroethane	CHCl ₂ CF ₃
2-chloro-1,1,1,2-tetrafluoroethane	CHClF ₂ CF ₃
Trichlorofluoroethane	C ₂ H ₂ FC ₃
Dichlorodifluoroethane	C ₂ H ₂ F ₂ Cl ₂
Chlorotrifluoroethane	C ₂ H ₂ F ₃ Cl
1-chloro-1-fluoroethane	CH ₃ CCl ₂ F
Chlorofluoroethane	C ₂ H ₄ FC ₂
Hexachlorofluoropropane	C ₃ HFCl ₆
Pentachlorodifluoropropane	C ₃ HF ₂ Cl ₅
Tetrachlorotrifluoropropane	C ₃ HF ₃ Cl ₄

TABLE III. Any research on substitute SF₆

Title research	Researcher	Year
Experiment on Breakdown Characteristics of SF ₆ /N ₂ Mixtures in Short Gap.	Xin, Lin Changwang, Shan	2015
Breakdown Characteristics of SF ₆ / CF ₄ Mixtures in Test Chamber and 25. 8kV GIS.	Park, Hwang, Chung-ho Ryul, Nam-Lee, Ki-taek Huh, Chang-su	2007
Analysis of the feasibility of CF ₃ I/CO ₂ used in C-GIS by partial discharge inception voltages in positive half cycle and breakdown voltages.	Zhang, Xiaoxing Xiao, Song Han, Yefei Dai, Qiwei	2015
Breakdown mechanism of different sulphur hexafluoride gas mixtures.	Onal, E.	2018

In Table II, there was much research that supports the Kyoto protocol but still used old SF₆ gas as the main medium to fill GIS, while to support the Kyoto Protocol program they used mixed gas as an active measure in reducing the amount of use of SF₆. The use of CF₃CHCl₂ gas as the main medium for substituting SF₆ gas is a pure effort to replace the total gas used in GIS equipment.

II. SPECIFICATION AND CHARACTERISTICS CF₃CHCl₂

The Kyoto Protocol recommended the utilization of one gas from the HCFC (Hydro Chloro Floro Carbons) family was CF₃CHCl₂ (Dichlorotrifluoroethane) gas could be seen in Table I. The selection of Dichlorotrifluoroethane gas was because it had the specifications, characteristics and capabilities such as SF₆ gas. The four requirements were recommended by the Protocol as alternative gases could be met by Dichlorotrifluoroethane gas. In addition to the four conditions that must be met by gas as a substitute for alternative gas, a more important requirement was the availability of gas in the market. The ease of gas procurement was very important so that market surveys were needed to see gas availability. Dichlorotrifluoroethane gas had elements VII-A (Halogen group) in its constituent chemical compounds, namely elements F (Flor) and Cl (Clor). The VIIA element was known to have electronegativity in its chemical structure elements. The elements were needed in the process of electric arc outages. We could see the capabilities and properties of Dichlorotrifluoroethane gas in the discussion below.

A. High Voltage (HV) Tests for CF₃CHCl₂

A breakdown voltage test was to obtain a real value of Dichlorotrifluoroethane gas if given voltage. Gas testing was carried out in a high voltage laboratory with equipment and set up of equipment as follows:

1. Prepare the test equipment was shown in Fig. 1. The equipment used had specifications: vacuum pump with VE180N type, Value brand with 230 VAC 50/60 Hz, a JEC-120 step-up transformer with 5 kVA capacities, Primary Voltage 100-200VAC, Secondary Voltage 50000 VAC.
2. Assembling the equipment/circuit HV tests was shown in Fig.1[21]

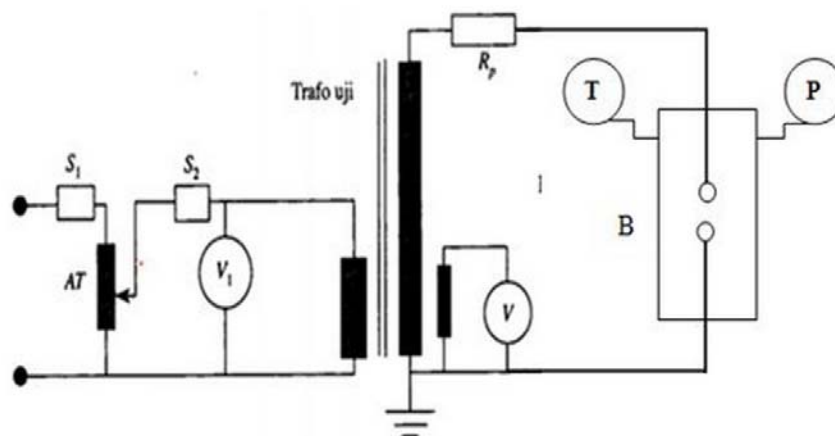


Fig.1 Circuit HV tests

Figure 1 showed the S1 and S2 automatically switches, AT Autotrafo, V Voltmeter, Rp Bump Resistor, Thermo-controlled, P Pressure (Bar), B Chamber Gas using feeder and outfeeder gas.

3. Preparing the chamber gas was by making a vacuum.
4. Test the CF_3CHCl_2 gas in the chamber was by adjusting the pressure (P), and the electrode gap (d) in the chamber.
5. Gives a voltage to the gas in space gradually from 0 kV was to increase until a breakdown occurs. The output voltage of the gas in the chamber was 2 kV/s.

The breakdown voltage in gas using Paschen law was an equation that provides breakdown voltage that was the voltage needed to start an electric arc between two electrodes in a gas as a function of pressure and gap [21] - [24].

We used Paschen's law (1) - (5) :

$$V_B = F (Pd) \tag{1}$$

$$V_B = f\left(\frac{E}{P}\right) Pd \tag{2}$$

$$V_B = \frac{BPd}{\ln\left(\frac{APd}{\ln\left(1 + \frac{1}{\gamma}\right)}\right)} \tag{3}$$

$$V_B = 2.718\left(\frac{B}{A}\right)\ln\left(1 + \frac{1}{\gamma}\right) \tag{4}$$

$$\frac{V_B}{Pd} = \frac{E_B}{P} = \frac{B}{\ln\left(\frac{APd}{\ln\left(1 + \frac{1}{\gamma}\right)}\right)} \tag{5}$$

B. Electronegativity in CF_3CHCl_2

Electronegativity was a number that showed the ability of an atom in a molecule to pull electrons into the atomic structure. The greater the electronegativity value of a compound was the greater the ability of the gas to extinguish the electric arc. Electronegativity was the affinity of an atom to attract electrons in a bond. Electronegativity affects polar pole formation in a chemical compound [22]–[25]. SF_6 gas and CF_3CHCl_2 gas had Halogen group elements which were groups of elements that had the greatest electronegativity value. Chemical elements found in SF_6 gas and CF_3CHCl_2 gas were elements F (Flor), Cl (Clor). Electronegativity values of the VIIA group were Flor 3.98, Clor 3.16, Brom 2.96, Iod 2.66, Astantin 2.2. We used the following equation to find the electronegativity value of a compound (6).

The electronegativity difference between two atoms A and B could be calculated by:

Dissociation Energy (Ed) A – B, A – A and B-B was expressed in electron volts. Factor (eV) $\frac{1}{2}$ was inserted to produce dimensionless values.

$$XA - XB = (eV)^{-\frac{1}{2}} \sqrt{\frac{Ed(AB) - (Ed[AA] + Ed[BB])}{2}} \quad (6)$$

C. Kyoto Protocol in CF₃CHCl₂

The Kyoto Protocol was an amendment to the United Nations Framework Convention on Climate Change, an international agreement on global warming. The results of the Kyoto Protocol Convention recommend replacement gas that was more environmentally friendly according to Table I. In addition to recommending a list of gases that were more environmentally friendly, the amendments also recommend the value of Global Warming Potential, Ozone Depleting potential and atmosphere live-time. The three conditions above were the conditions that must be owned by a replacement gas.

The gas value used a value base:

1. Global Warming Potential (GWP) was an index system that compares the potential of a greenhouse gas to heat the earth, compared to the potential of carbon dioxide [26]. The GWP value could be obtained by the equation (7):

$$GWP_i = \frac{\int_0^{TH} R F_i(t) dt}{\int_0^{TH} R F_r(t) dt} = \frac{\int_0^{TH} a_i [C_i(t)] dt}{\int_0^{TH} a_r [a_r(t)] dt} \quad (7)$$

RF_i = Radiative forcing (RF) for element i, RF_r = Radiative forcing the reference gas (CO₂), TH = the time horizon, C_i = the time-dependent abundance of the element i, a_i = the RF per unit mass increased in atmospheric abundance of component i (radiative efficiency), a_r = the RF per unit mass increased in atmospheric abundance of reference component.

2. Ozone Depleting Potential (ODP) was a relative measure of the ozone layer degradation caused by a compound. ODP was the comparative value of ozone layer degradation of a compound in certain mass units of CFC-11 with the same mass [27]. Calculate the ODP value with the equation (8) as follows:

$$ODP = \frac{\text{Global } \Delta O_3 \text{ due to substance } i}{\text{Global } \Delta O_3 \text{ due to CFC - 11}} \quad (8)$$

3. Atmosphere Live-time (ALT) was the average time that a molecule resided in the atmosphere before it was removed by the chemical reaction or deposition reaction [28], [29]. This could also be thought of as the time that it took after the environment had returned to natural levels. Greenhouse gas live-times could range from a few years to a few thousand years. ALT values could be obtained by equation (9)

$$ALT = \frac{\text{mass}}{\text{removal rate}} = \frac{m}{F_{out} + L + D} \quad (9)$$

m = mass (kg), F_{out} = Flow of substance x out the box (kg/year), L = loss of substance x (kg/year), D = deposition of substance x (kg/year)

D. Techno-Economic SF₆ Versus CF₃CHCl₂

The use of new gas as a substitute for SF₆ gas could not be separated from the economic value considered by the market to accept CF₃CHCl₂ gas as a new medium for SF₆ gas substitution [30], [31]. Economic values that form the basis of consideration were:

1. The price of providing replacement gas materials.
2. Price/transportation costs from producers to consumers.
3. Availability/ease of material on the market.
4. Reliability of new gas.

One of the main components of techno-economic values were procurement costs, availability of material in the market and reliability of gas replacement. The factor of procurement of gas materials was very vital because it involved 40% of the costs incurred by consumers. Prices were based on prevailing market price standards. The benchmark gas market price could be shown in Table III.

TABLE III. Pricelist any Gas

Gas	Pricelist/kg
SF ₆	IDR 1,554,800
CF ₃ CHCl ₂	IDR 300,000
N ₂	IDR 70,000
CO ₂	IDR 2,240
Argon	IDR 29,685

The benchmark for gas procurement prices could be seen in Table III, which was a benchmark price for some gas in the territory of the Republic of Indonesia.

III. RESULT AND DISCUSSION

1. Results of HV Tests were shown in Table IV.

TABLE IV. Breakdown Voltage CF₃CHCl₂ using HV tests

P (Bar)	d (mm)	T (Celcius)	Breakdown Voltage (kV)					Average
			1	2	3	4	5	
0.1	1	25	13.8	12.9	13.9	12.8	13.1	13.3
0.1	1	30	13.8	12.8	12.1	11.8	11.6	12.42
0.1	1	40	11.9	11.9	12.6	11.6	11.8	11.96
0.1	1	50	13.9	12.9	14.9	14.6	13.3	13.92
0.1	2	25	24.8	23.9	24.9	23.8	24.5	24.38
0.1	2	30	24.6	24.7	24.9	24.4	21.2	23.96
0.1	2	40	24.3	23.4	23.8	21.8	21.9	23.04
0.1	2	50	25.6	23.6	26.8	26.9	25	22.58
0.1	3	25	37.7	36	37.9	36.4	37.2	37.04
0.1	3	30	37.6	36.8	36.1	32.9	32.6	35.2
0.1	3	40	34.6	34.8	36	34.6	34.8	34.96
0.1	3	50	37.9	36.9	39.8	39.2	38.5	38.46
0.1	4	25	-	-	-	-	-	-
0.1	4	30	-	-	-	-	-	-
0.1	4	40	-	-	-	-	-	-
0.1	4	50	-	-	-	-	-	-
0.2	1	25	26.6	26.6	27.4	24.4	24.9	25.98
0.2	1	30	23.3	23.3	22.4	23.8	22.9	23.14
0.2	1	40	23.3	19.9	21.6	20.7	24.9	22.08
0.2	1	50	28.3	28.3	27.4	29.1	26.3	27.88
0.2	2	25	-	-	-	-	-	-
0.2	2	30	-	-	-	-	-	-
0.2	2	40	-	-	-	-	-	-
0.2	2	50	-	-	-	-	-	-

The results of data collection during the test 5 times obtained the average value of the voltage disturbance CF₃CHCl₂ in Table IV :

1. The test by changing the gas pressure in the chamber showed the ability of the gas to withstand a breakdown voltage of 11.96 kV at a pressure of 0.1 Bar and 22.08 kV at a pressure of 0.2 Bar. The result of this study there was an increase 1.8 times in breakdown voltage compared to the chamber pressure at position 0.1 bar.
2. Testing by changing the electrode distance at a pressure of 0.1 bar obtained a breakthrough voltage of 11.96 kV at a gap of 1 mm, 22.58 kV at a gap of 2mm and 34.96 kV. When the gap was changed at the 3 mm there was an increase 1.5 times in breakdown voltage compared to when the electrode gap was 1 mm.

- Testing by changing the temperature in the room did not show a significant change. Testing by changing/affecting the chamber temperature could be ignored because it did not show significant changes, Comparison of testing experimental and theoretical details emphasizes according to Paschen's law with equations (1) - (5) was shown in Table V.

TABLE V. Deviation of Breakdown Voltage CF_3CHCl_2

P (Bar)	d (mm)	Breakdown Voltage (kV)		Deviation of Breakdown Voltage (%)
		Paschen Law	Experiment	
0.1	1	9.5	11.96	25.89
0.1	2	18.35	22.58	23.05
0.1	3	27.2	34.96	28.53
0.1	4	36.05	-	-
0.2	1	19	22.08	16.21
0.2	2	36.05	-	-

Table V showed the breakdown voltage deviation of 16.21% - 28.53% between theories compared to the experimental results. The HV test showed the breakdown voltage of SF_6 gas at 90 kV / bar and CF_3CHCl_2 gas at 119.6 kV / bar [32]–[34].

If both gases (SF_6 and CF_3CHCl_2) were inserted into the chamber on GIS equipment with a 7 Bar gas pressure then the breakdown voltage for SF_6 gas was 630 kV and the breakdown voltage for CF_3CHCl_2 gas was 837 kV. Both gases were able to withstand breakdown voltages above 500 kV. Because it was able to withstand breakdown voltage above 500 kV, CF_3CHCl_2 gas was very potential to be used as a substitute for SF_6 gas.

- The electronegativity value obtained from equation (6) is that SF_6 gas had an electronegativity value of 3.98 while the CF_3CHCl_2 gas had an electronegativity value of 7.14. The greater the electronegativity value of the material, the faster the material in the process of electric arc outages when switching on GIS equipment. The CF_3CHCl_2 gas had the ability to reduce fire arcs 1.7 times compared to SF_6 gas.
- The values of GWP, ODP, and Alt that were owned by SF_6 gas and CF_3CHCl_2 gas were:
 - The GWP value of two gases according to equation (7) was that SF_6 gas had a value of 23900 times that of CO_2 gas, while the GWP value of CF_3CHCl_2 gas had a value of 23 times CO_2 gas.
 - The ODP value of two gases according to equation (8) was that SF_6 gas has a value of 0.08 times that of CO_2 gas, while the ODP value of CF_3CHCl_2 gas had a value of 0.016 times the gas from CO_2 gas.
 - The Alt value of two gases according to equation (9) was that SF_6 gas had an Alt value of 3200 years while CF_3CHCl_2 gas had an Alt value of 1.5 years.
- For GIS tubes with 7 Bar pressure on substation equipment, 210 kg of gas was needed. Based on Table III, which was the price of gas in Indonesian currency, namely rupiah (IDR), the gas procurement price for SF_6 gas was 326,508,000 IDR, while the cost required to obtain CF_3CHCl_2 gas was Rp. 63,000,000. The cost required to obtain gas for an operating voltage of 500 kV, CF_3CHCl_2 gas was 0.2 times cheaper than SF_6 gas

IV. CONCLUSION

The CF_3CHCl_2 gas is very feasible to be recommended as a new alternative gas to replace SF_6 gas for GIS equipment in substations.

The CF_3CHCl_2 gas is very suitable to be used as a new alternative to replace SF_6 gas because it has the ability to withstand a breakdown voltage above 500 kV and has a better breakdown voltage than SF_6 gas, which is able to withstand breakage voltage of 1.3 times greater than SF_6 gas.

The CF_3CHCl_2 gas has capabilities that are more environmentally friendly than SF_6 gas and in accordance with the requirements of the Kyoto protocol convention for environmentally friendly values which include the value of the Global Warming Potential, the Ozone Depleting Potential value and the live-time Atmosphere value. The overall value of CF_3CHCl_2 gas has a better value than the value of SF_6 gas.

The techno-economic value in terms of procurement of goods shows that the procurement price of CF_3CHCl_2 gas reaches IDR 63,000,000 is cheaper than compared to the procurement of SF_6 gas which reaches IDR 326,508,000.

In the future, CF_3CHCl_2 gas is very potential, it is recommended for alternative replacements in GIS equipment and has the values needed as a requirement for gas insulation, fire arc extinguisher, ability to withstand penetrating stresses and values required as environmentally friendly gas compared to SF_6 gas.

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