JAREE-Journal on Advanced Research in Electrical Engineering
Volume 3, Number 1, April 2019

Breakdown Characteristic of CF_3CHCl_2 / 10-30% CO_2 Gas Mixture Based on Its Bonding Energy

Tedy Juliandhy
Department of Electrical Engineering
Universitas *Gadjah Mada*,Yogyakarta, Indonesia
juliandhy2@gmail.com; tedy.s3te14@mail.ugm.ac.id

T. Haryono
Department of Electrical Engineering
Universitas *Gadjah Mada*, Yogyakarta, Indonesia
thr@te.ugm.ac.id

Eka Firmansyah
Department of Electrical Engineering
Universitas *Gadjah Mada*, Yogyakarta, Indonesia
eka.firmansyah@ugm.ac.id

Indra Perdana
Department of Chemical Engineering
Universitas Gadjah Mada, Yogyakarta, Indonesia
iperdana@ugm.ac.id

***Abstract*— Sulfur hexafluoride gas according to the Montreal Protocol and Kyoto protocol needs to be limited and gradually reduced because it causes global warming, the greenhouse effect and acid rain on the environment. The Kyoto protocol recommends the use of dichlorotrifluoroethane gas as one of the alternatives to substitute sulfur hexafluoride gas. This research discusses the use of dichlorotrifluoroethane gas mixed with CO_2 gas which was known to be able to withstand the breakdown voltage of 680-837 kV. This research discusses the comparison of breakdown voltage values and differences in breakdown voltage deviation between bond energy theory and high voltage testing. The dichlorotrifluoroethane gas has a price of 5.18 times cheaper than hexafluoride sulfur gas. The ability of dichlorotrifluoroethane gas to insulation gas in gas insulated switchgear needs to be applied as a real potential substitute for sulfur hexafluoride gas.**

Keywords- Sulfur Hexafluoride, dichlorotrifluoroethane, bond energy, Paschen's law, Techno-economy, Gas Insulated Switchgear

I. INTRODUCTION

This SF_6 (sulfur hexafluoride) gas has the ability to extinguish electric arcs and capabilities as gas isolation in GIS (Gas Insulated Switchgear) equipment[1]–[8]. One of the chemical elements of SF_6 gas is class VII-A (halogen). The halogen group is known to have electronegativity and the ability to extinguish the electric arc. The halogen chemical element that is owned by SF_6 is element F (Fluor). The Kyoto protocol limits the use of SF_6 gas because it is known to be a source of global warming and the greenhouse effect [9]–[16]. The Kyoto protocol recommends several gases as alternative substitutes as shown in Table I.

One of the gases suggested by the Kyoto protocol is CF_3CHCl_2 (dichlorotrifluoroethane) gas. This research discussed SF6 gas substitution by testing CF_3CHCl_2 + CO_2 gas. Research also discussed breakdown voltage comparisons using the bonding energy calculation versus high voltage test. The CF_3CHCl_2 gas has 2 halogen elements in its compounds, namely elements F (Fluorine) and Cl (Chlorine).

TABLE I. GAS RECOMMENDED KYOTO PROTOCOL

Chemical	Chemical Formula
Dichlorotrifluoroethane	$CHCl_2CF_3$
2-chloro-1,1,1,2-tetrafluoroethane	$CHClFCF_3$
Trichlorofluoroethane	$C_2H_2FCl_3$
Dichlorodifluoroethane	$C_2H_2F_2Cl_2$
Chlorotrifluoroethane	$C_2H_2F_3Cl$
Dichlorofluoroethane	$C_2H_3FCl_2$
1,1-dichloro-1-fluoroethane	CH_3CCl_2F
Chlorodifluoroethane	$C2H_3F_2Cl$
1-chloro-1,1-difluoroethane	CH_3CClF_2
Chlorofluoroethane	C_2H_4FCl
Hexachlorofluoropropane	C_3HFCl

This research discussed the use of CF_3CHCl_2 gas as an alternative to SF_6 gas. The method used in analyzing the ability of CF_3CHCl_2 gas as a potential gas replacement for SF_6 with bond energy and HV test methods. The purpose of mixing the main gas with CO_2 was to reduce the main gas concentration if it leaks in the air because there is no 100% gas that does not cause natural effects, also to reduce the gas procurement costs that arise for the supply of gas at the substation. In addition to analyzing the ability of CF_3CHCl_2 gas as a gas isolation medium, it also discusses the Kyoto protocol value in gas as well as the technology of the CF_3CHCl_2 gas compared to SF_6 gas.

II. METHODOLOGY AND ANALYSE RESEARCH

There are 8 important points of gas which are the basis of environmentally friendly gas as contained in the results of the Kyoto protocol, as gas isolation material and fillers of GIS equipment so that they can be accepted in the market to replace SF_6 gas, namely:

1. Electronegativity
2. Global Warming Potential
3. Ozone Depleting Potential
4. Live-time atmosphere
5. Breakdown Voltage using Bond Energy calculation
7. High Voltage (HV) tests and Setup experimental
8. Techno-economic

A. Electronegativity

The more electronegative the molecule will tend to bind electrons to form negatively charged molecules [17]–[21]. The electronegative nature of CF_3CHCl_2 as well as in SF_6 is what causes it to become a bad current conductor. The greater the electronegativity value of the chemical element, the greater the ability of the gas to resist breakdown voltage. Electronegativity is related to the speed of extinguishing an arc of fire. The greater the electronegativity value of a chemical element, the quickly chemical elements are able to extinguish the electric arcs that occur due to the switching process in GIS equipment. The value of electronegativity can be found by equation (1) [22].

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

where, Dissociation Energy (Ed) A – B, A – A and B-B was expressed in electron volts. Factor $(\mathrm{eV})^{½}$ was inserted to produce dimensionless values [23].

B. Global Warming Potential (GWP)

Global warming potential [24] relates to the potential for a compound to have a long-term effect on global warming. GWP can be searched by equation (2) [25]:

$$\mathrm{GWP_i} = \frac{\int_0^{\mathrm{TH}} \mathrm{R\,F_i(t)dt}}{\int_0^{\mathrm{TH}} \mathrm{R\,F_r(t)dt}} = \frac{\int_0^{\mathrm{TH}} \mathrm{a_i\,[C_i(t)]dt}}{\int_0^{\mathrm{TH}} \mathrm{a_r\,[a_r(t)]dt}} \quad (2)$$

where RFi is Radiative forcing (RF) for element i, RFr is Radiative forcing the reference gas (CO_2), TH is the time horizon, Ci is the time-dependent abundance of the element i, ai is the RF per unit mass increased in atmospheric abundance of component i (radiative efficiency), ar is the radiative forcing per unit mass increased in atmospheric abundance of reference component.

C. Ozone Depleting Potential (ODP)

Ozone Depleting Potential relates to the potential of gas compounds that can cause depletion of the ozone layer over a period of time [26], [27]. To get the ODP value can be obtained using equation (3) [25]:

$$\mathrm{ODP} = \frac{\text{Global } \Delta O_3 \text{ due to substance i}}{\text{Global } \Delta O_3 \text{ due to CFC} - 11} \quad (3)$$

The Ozone Depletion Potential is a relative index that expresses the potential to destroy ozone over its lifetime in the atmosphere compared to the effect of CFC-11. Therefore, the OPD of CFC-11 is set to be 1. The ODP of a compound is the ratio of the impact on ozone of a chemical compared to the impact of a similar mass of CFC-11.

D. Atmosphere Live-time (ALT)

The last point needed as a gas requirement that meets the Kyoto protocol is Atmospheric Live-Time (ALT). Live-time atmospheric values can be obtained by equation (4) [25].

$$\mathrm{ALT} = \frac{\text{mass}}{\text{removal rate}} = \frac{\mathrm{m}}{\mathrm{F_{out}} + \mathrm{L} + \mathrm{D}} \quad (4)$$

where m is mass (kg), F_{out} is a flow of substance x out the box (kg/year), L is a loss of substance x (kg/year), D is deposition of substance x (kg/year).

E. Breakdown voltage using bond energy calculation

Bond energy is the energy needed to separate bonds between atoms in a molecule. The greater the bond energy possessed by a compound, the greater the energy required to separate the bonds of the compound. When a chemical reaction occurs, the molecular bonds are cut off and then the other molecules will form. If the energy that holds the bonds together is stronger, then big energy is needed to separate them.

TABLE II. STANDART BOND ENERGY [28], [29]

Bond	**Energy (kJoule/mol)**	**Bond**	**Energy (kJoule/mol)**
C--C	348	H--I	299
C--H	413	H--C	413
C--N	293	H--N	391
C--O	358	H--O	366
C--F	485	H--H	436
C—Cl	328	O—O	145
C—Br	276	O—H	463
C—I	240	O—F	190
C—S	259	O—Cl	203
Si—H	323	O—I	234
Si—Si	226	S—H	339
Si—C	301	S—F	327
Si—O	368	S—Cl	253
N—H	391	S—Br	218
N—N	170	S—S	266
N—O	201	F—F	158
N—F	272	Cl-Cl	243
N—Cl	200	Cl—F	253
N—Br	243	Br-Br	193
I----Cl	208	Br---F	237
I---Br	175	Br---Cl	218
I----I	151	Br---P	65

Table II shows the energy value between compounds. If the compound bond is high, it has strong bonds and the molecule will be more stable and less reactive. Reactive compounds have bond energy, which is generally lower. The value of bond energy is obtained by using equation (5) [30]:

$$E_{bond} = \Delta E_{elstat} + \Delta E_{Pauli} + \Delta E_{oi} \quad (5)$$

where E_{elstat} is an electrostatic interaction calculated using uninterrupted fragment density, E_{Pauli} is an energy change caused by orthogonalization of the function of fragment waves and E_{oi} arises from recombination of orthogonalized orbital fragments to form supermolecular wave functions.

To change the bond energy into a breakdown force, it is necessary to convert it as in equation (6) and (7).

$$V = \frac{E}{Q} \quad (6)$$

The voltage V in volts (V) is equal to the energy E in electron-volts (eV), divided by the electric charge Q in elementary charge or proton/electron charge (e):

$$V_B = \frac{eV}{e} \quad (7)$$

Joules per mole, J mol^{-1}, is an SI publication unit for energy per number of materials. Energy is measured in units of joules, and the amount of material is calculated in units of moles. 1 kJ mol^{-1} is equal to 0.239 kcal mol^{-1} or 1.04x10^{-2} eV, 1 mol is equal 6x10^{23} for each ingredient. The value of energy conversion can be seen in Table III.

TABLE III. VALUE OF ENERGY CONVERSION

	Joule	Calorie	eV
Joule	1	0.2389	6.242x10^{18}
Calorie	4.186	1	2.613x10^{19}
eV	1.6x10^{-19}	3.8x10^{-20}	1

The amount of bond energy for mixed gases is obtained by equation (8) [25].

$$P_{Gas\ mixture} = P_{CF3CHCl2} + P_{CO2} \quad (8)$$

where P gas mixture is total pressure of the gas mixture, $P_{CF3CHCl2}$ is partial pressure of CF_3CHCl_2 gas and P_{CO2} is partial pressure of CO_2 gas.

Based on equation (6), a formula can be made that connects all of them to obtain a breakdown voltage based on bond energy. The breakdown voltage formula based on bond energy can be seen in the description below.

Percentage of bond energy gas (E_{Total}) is (equation 9):

$$E_{Total} = E_1 + E_2 + \cdots + E_n \quad (9)$$

where, E_{Total} is the percentage of total bond energy, E_1 percentage of gas to 1 times the gas bond energy to 1, E_2 the percentage of gas to 2 times the gas bond energy to 2 and E_n is the percentage of gas to n multiplied by the gas bond energy to n. While the magnitude of the breakdown voltage is in accordance with equation (10) - (12).

$$V = f(V) \quad (10)$$

$$V_B = f\left(\frac{E}{Q}\right) \quad (11)$$

$$V_B = \left(\frac{E_1 + E_2 + \ldots + E_n}{Q}\right) \quad (12)$$

If the charge (Q) has a value of 226.72x10^{-6} electrons, then the formula above can be reduced to equations.

where V_B showing breakdown voltage with volt (V), E_1 the amount of bond energy multiplied by percentage in gas material to 1 in eV, E_2 the amount of bond energy multiplied by percentage in gas material to 2 in units of eV, and large E_n the bond energy is multiplied by the percentage in the gas material to n in eV units.

Based on the description of the formula (10) - (12) above. The breakdown voltage can be made a prediction based on bond energy.

F. *High Voltage tests and Setup experimental*

The purpose of testing HV tests is to compare the results of predictions between the breakdown voltage values with the bond energy method with the breakthrough value of the Paschen law method through real HV test testing. In addition, it is also to see the breakdown voltage values both of the bond energy method and the Paschen's law. By comparing the two methods with HV test testing, it is expected that the right and most precise method of choice can be done to predict the breakdown stress of an insulating material. Setup experimental, the tools used in HV testing tests include:

The vacuum pump is used to make a vacuum chamber. Specifications of vacuum pump: value brand, voltage 230 VAC /50-60 Hz, Model VE180N, motor 0.75 HP, transformer testing with specifications, type JEC-120, Capacity 5 kVA, primary voltage 100-200 VAC/secondary voltage 50000VAC, Made in Tokyo Transformer Co.Ltd, gas chamber with dimensions of 70 cm x 70 cm x 90 cm to place test electrode and test gas, thermometer indoor temperature gauge Gas in chamber, barometer to measure pressure and volume of gas and gas heater 100 Watt. Perform a vacuum chamber as shown in Figure 1.

Fig. 1. Vacuum chamber process

After vacuum testing, the HV test was carried out of the chamber to determine the chamber's ability to withstand the breakdown voltage as showed in Figure 2.

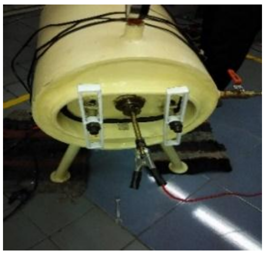

Fig. 2. HV test chamber process

After testing the chamber, a circuit HV test was performed as showed in Figure 3 [31].

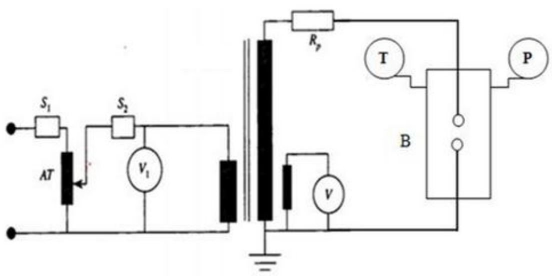

Fig. 3. HV test circuit [32], [33]

Figure 3 showed the S1 and S2 automatically switches, AT autotransformer, V voltmeter, Rp bump resistor, T is thermo-controlled, P Pressure (Bar), B Chamber Gas using feeder and out-feeder gas.

G. Techno-economic CF_3CHCl_2 as an Insulation Material

Techno-economic studies include the application and control of the use of dichlorotrifluoroethane (CF_3CHCl_2) gas [34]–[37]. It is undeniable that the existence of new alternative gas must have a general requirement that new technologies can be accepted by the user community. Terms of new technology can be accepted by the community are: technology is simple and easy to use, cheap and easy to obtain, reliable technology to use, and cheap and cheap technology in its maintenance. This manuscript discusses the costs of gas procurement as a comparison to the costs of gas procurement SF_6 as a gas isolation medium in GIS equipment.

III. Result and Discussion

The HV test results can be seen in Table 4.

TABLE IV. HIGH VOLTAGE TESTS RESULT (CF_3CHCL_2 +CO_2)

P (Bar)	d (mm)	T (°C)	Breakdown Voltage (kV)				
			100%	90%	80%	70%	60%
0.1	1	25	13.3	12.44	11.08	9.04	8.46
0.1	1	30	12.42	11.68	11.28	10.42	8.68
0.1	1	40	11.96	10.64	10.08	11.04	9.24
0.1	1	50	13.92	13.42	11,92	11.42	9.68
0.1	2	25	24.38	24.12	21.54	19.12	18.12
0.1	2	30	23.96	23.34	21.74	19.54	18.34
0.1	2	40	24.04	23.32	21.86	19.82	18.48
0.1	2	50	24.58	23.42	22.58	20.42	19.62
0.1	3	25	37.04	35.64	31.78	29.64	24.46
0.1	3	30	35.2	34.84	32.66	30.26	24.84
0.1	3	40	34.96	34.48	34.08	30.98	25.08
0.1	3	50	38.46	36.34	34.94	31.40	25.34
0.2	1	25	25.98	24.18	22.36	20.78	18.78
0.2	1	30	25.14	24.82	22.82	21.04	19.64
0.2	1	40	25.08	24.22	23.02	21.22	20.22
0.2	1	50	27.88	26.18	24.18	22.8	21.18
0.2	2	25	-	46.48	41.56	31.42	28.34
0.2	2	30	-	46.88	41.88	39.06	28.56
0.2	2	40	-	47.3	42.22	40.38	28.84
0.2	2	50	-	47.52	42.58	41.76	30.2

Bond energy by mixing CF_3CHCl_2 + CO_2 gas using equation (5) and Standart of value bond energy Calculation of bond energy can be described as follows [29]:

- Bond Energy CF_3CHCl_2 :
  3 (C---F) = 3 (485 kJ/mol) = 1455 kJ/mol
  2 (C---Cl) = 2 (328 kJ/mol) = 656 kJ/mol
  C---H = 1 (413 kJ/mol) = 413 kJ/mol
  Bond energy CF_3CHCl_2
  (1455 + 656 +413) kJ/mol = 2524 kJ/mol.
- Bond energy CF_3CHCl_2 + CO_2
  3(C-F) = (3x485) kJ/mol = 1455 kJ/mol
  2(C-Cl) = (2x328) kJ/mol = 656 kJ/mol
  C-H = 423 kJ/mol
  C-O = (2x358) = 716 kJ/mol
  Bond Energy CF_3CHCl_2 +CO_2
  (1455 + 656 +423+716) kJ/mol = 3250 kJ/mol.

In the same way, it can be obtained that the value of bond energy in other mixed gases can be seen in Table 5.

TABLE V. BOND ENERGY CALCULATION

Gas	Bond energy (kJ/mol)
CO_2	716
SF_6	1962
CF_3CHCl_2	2524
90% CF_3CHCl_2+10% CO_2	2343.2
80% CF_3CHCl_2+20% CO_2	2162.4
70% CF_3CHCl_2+30% CO_2	1981.6

Breakdown voltage using equations (12) and data bond energy in the Table V obtained results:

- Breakdown voltage 100% CF_3CHCl_2
  V_B = (2524 x 1.04 x 10^{-2}) : 226.72x10^{-6} = 115775.88 volt
- Breakdown voltage 90% CF_3CHCl_2 + 10% CO_2
  V_B= ([0.9x2524x1.04x10^{-2}] + [0.1x716x1.04x10^{-2}]) : 226.72x10^{-6} = 107482.58 volt
- Breakdown voltage 80% CF_3CHCl_2 + 20% CO_2
  V_B= ([0.8x2524 x 1.04 x 10^{-2}] + [0.2x716 x 1.04 x 10^{-2}]) : 226.72x10^{-6} = 99189.29 volt
- Breakdown voltage 70% CF_3CHCl_2 + 30% CO_2
  V_B= ([0.7x2524 x 1.04 x 10^{-2}] + [0.3x716 x 1.04 x 10^{-2}]) : 226.72x10^{-6} = 90895.99 volt
- Breakdown voltage 60% CF_3CHCl_2 + 40% CO_2
  V_B= ([0.6x2524 x 1.04 x 10^{-2}] + [0.4x716 x 1.04x 10^{-2}]) : 226.72x10^{-6}= 82602.69 volt

Breakdown voltage value using bond energy data compared to the results of high voltage testing (retrieve data at the lowest range value in Table IV) can be seen in Table VI.

TABLE VI. BREAKDOWN VOLTAGE BOND ENERGY VERSUS HV TEST

Gas	Breakdown voltage (kV)	
	Bond Energy	HV test
100% CF_3CHCl_2	115.78	119.6
90% CF_3CHCl_2+10% CO_2	107.48	106.4
80% CF_3CHCl_2+20% CO_2	99.19	100.8
70% CF_3CHCl_2+30% CO_2	90.89	90.4

Deviation of breakdown voltage using bond energy and HV test can show in Table VII. Breakdown value of gas voltage under pressure 1 bar and gap electrode 1mm.

TABLE VII. DEVIATION BREAKDOWN VOLTAGE BOND ENERGY VERSUS HV TEST

Gas	Breakdown voltage (kV)		Deviation (%)
	Bond energy	HV test	
100% CF_3CHCl_2	115.78	119.6	3.29
90%CF_3CHCl_2+10%CO_2	107.48	106.4	1
80% CF_3CHCl_2+20%CO_2	99.19	100.8	1.62
70% CF_3CHCl_2+30%CO_2	90.89	90.4	0.54

If SF_6 gas is needed in GIS equipment using a pressure of 7 bars, the operational voltage of SF_6 gas at a pressure of 7 bar is 90 kV x 7 bar = 630 kV. The ability of SF_6 gas with a GIS 7 bar pressure is able to withstand a breakdown voltage of 630 kV which is very suitable for use at the most optimal working voltage of 500 kV. So if it is assumed by conditioning the CF_3CHCl_2 gas like SF_6 gas using a pressure of 7 bar and calculating it with the bond energy method, then the CF_3CHCl_2 + CO_2 gas is obtained through the breakdown voltage at 7 bar (Table VIII):

TABLE VIII. BREAKDOWN VOLTAGE CF3CHCL2 + CO2

Gas	Breakdown Voltage (kV)
SF_6	630
100% CF_3CHCl_2	837
CF_3CHCl_2 + 10% CO_2	870.8
CF_3CHCl_2 + 20% CO_2	775.6
CF_3CHCl_2 + 30% CO_2	680.4

For environmentally friendly gas requirements in accordance with the Kyoto protocol, the following values are obtained:

1. The electronegativity value of SF_6 gas compared with CF_3CHCl_2 gas using equation (1) obtained a value, SF_6 of 3.98 and CF_3CHCl_2 gas of 7.14. The greater the electronegativity value, the more the material is not a good conductor or a good insulator. In addition, the higher the electronegativity value, the better and faster the gas material is in extinguishing the electric arc during the switching process.
2. GWP value based on equation (2) obtained a value of GWP SF_6 of 23900 and GWP value of CF_3CHCl_2 gas of 23. The greater the GWP value, the greater the potential or effect on global warming.
3. ODP gas value based on equation (3) obtained SF_6 gas of 0.8 while the ODP value of CF_3CHCl_2 gas was 0.016. The greater the ODP value of the gas material, the greater the potential depletion of the ozone layer if the gas material is released in the air.
4. ALT value on gas using equation (4) obtained ALT value of SF_6 gas for 3200 years while CF_3CHCl_2 gas has an ALT value of 1.5 years. The higher the ALT value of a material, the longer it will stay in the atmosphere. So SF_6 gas requires longer recovery time in the atmosphere than CF_3CHCl_2 gas.

Techno-economic is 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 list could be shown in Table IX.

TABLE IX. PRICELIST PROCUREMENT OF COSTS

Gas	Pricelist/kg
SF_6	IDR 1,554,800
CF_3CHCl_2	IDR 300,000
N_2	IDR 70,000
CO_2	IDR 2,240
Argon	IDR 29,685

Table IX shows the price of gas procurement per kg in the territory of the Republic of Indonesia. For a 500 kV GIS compartments, the main gas is about 210kg of gas. If it is assumed that the amount of gas needed is the same as the breakdown voltage that can be resisted, the breakdown voltage compared to the cost of gas procurement can be shown in Table X.

TABLE X. BREAKDOWN VOLTAGE VERSUS PROCUREMENT OF COSTS

Gas	Breakdown Voltage (kV)	Procurement of costs (IDR)
SF_6	630	326,508,000
CF_3CHCl_2	837	63,000,000
CF_3CHCl_2 + 10% CO_2	870.8	56,747,040
CF_3CHCl_2 + 20% CO_2	775.6	50,490,080
CF_3CHCl_2 + 30% CO_2	680.4	44,241,120

From Table X, it can be seen that with the ability to withstand breakdown voltage at a working voltage of 500 kV, SF_6 gas requires a fee of IDR 326,508,000 while CF_3CHCl_2 gas requires a cost of IDR 63,000,000. The cost of procuring CF_3CHCl_2 gas as insulation material on GIS equipment is 5.18 times cheaper than the cost of gas for SF_6. For GIS filler gas with CO_2 gas mixed, the optimal percentage is 30% for a 500 kV working voltage. For a working voltage of 500 kV against the procurement costs versus the ability to withstand breakdown voltage, the researchers suggested that the gas mixture be 70% CF_3CHCl_2 + 30% CO_2. When compared with SF_6 gas, the gas mixture is 70% CF_3CHCl_2 + 30% CO_2, so the cost of gas procurement is cheaper by 7.38 time compared to SF_6 gas procurement.

IV. CONCLUSION

Based on the testing and discussion that have been done, a conclusion can be made as follows:

The results of the calculation using the bond energy method and high voltage testing using bond energy data obtained the bond energy gas value CF_3CHCl_2 (2524 kJ / mol) better than SF_6 gas (1962 kJ / mol). If it is assumed that the two gases are applied to a 500 kV GIS equipment with a compartment pressure of 7 bar, the ability to withstand CF_3CHCl_2 gas breakdown voltage is 837 kV / 7 bar, while SF_6 gas has the ability to withstand a breakdown voltage of 630 kV / 7 bar. The value of bond energy can be used as a basis for predicting the value of breakdown voltage in gas (both pure gas and mixed conditions).

The use of bond energy calculations can produce a breakdown voltage value with a breakdown voltage deviation value below 3%.

Mixing CF_3CHCl_2 + gas CO_2 gas (maximum 30% CO_2 gas) is able to operate at the operational voltage on a 500 kV Gas insulated switchgear compartment because it can withstand breakdown voltage of 680 kV.

The techno-economic value of CF_3CHCl_2 gas as an alternative gas substitute for SF6 gas has an economic value at a price of 5.18 times cheaper than SF_6 gas.

For environmentally friendly gas and according to the Kyoto protocol recommendations, a better value is obtained compared to SF_6 gas.

In the future, CF_3CHCl_2 gas will need to be intensively developed and immediately applied for filling material for GIS equipment as an insulating gas substitute for SF_6 gas.

ACKNOWLEDGEMENT

This work was supported by Department of Electrical Engineering and Information Technology, and Department of Chemical Engineering, Gadjah Mada University. The researchers are thankful for the financial support from Hang Tuah University.

REFERENCES

[1] Y. Kieffel, F. Biquez, P. Ponchon, and T. Irwin, "SF6 alternative development for high voltage switchgears," *2015 IEEE Power Energy Soc. Gen. Meet.*, no. June, pp. 1–5, 2015.

[2] C. Wang, Y. Tu, X. Li, and R. Tan, "Performance of flashover on the resin spacer surface in N2/SF6 and SF6/air gas mixture under AC power frequency," *2012 IEEE Int. Symp. Electr. Insul.*, pp. 141–144, 2012.

[3] J. H. Lee, J. S. Ryu, H. W. Joo, S. J. Tak, S. W. Park, and J. H. Lee, "Insulation characteristics of various conditions for eco-friendly high voltage switchgear," in *The XIX International Conference on Electrical Machines - ICEM 2010*, 2010, pp. 1–4.

[4] A. Bastian, D. S. Rahmani, and A. Muchtar, "Developing norm for SF6 quality of tropical GIS," *Proc. 2012 IEEE Int. Conf. Cond. Monit. Diagnosis, C. 2012*, vol. 2, no. September, pp. 454–457, 2012.

[5] X. Zhang, F. Meng, and B. Yang, "Use of hydroxyl-modified carbon nanotubes for detecting SF6 decomposition products under partial discharge in gas insulated switchgear," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 6, pp. 2246–2253, Dec. 2013.

[6] X. Zhang, S. Xiao, Y. Han, and Q. Dai, "Analysis of the feasibility of CF3I/CO2used in C-GIS by partial discharge inception voltages in positive half cycle and breakdown voltages," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 6, pp. 3234–3243, 2015.

[7] S. A. Ward, M. A. Abd Allah, and A. A. Youssef, "Particle intiated breakdown inside gas insulated switchgear for various gases mixtures," *Int. J. Electr. Eng. Informatics*, vol. 4, no. 2, pp. 320–334, 2012.

[8] T. A. Paul, M. Porus, B. Galletti, and A. Kramer, "SF6 concentration sensor for gas-insulated electrical switchgear," *Sensors Actuators, A Phys.*, vol. 206, pp. 51–56, 2014.

[9] Y. Liu, Z. Zhou, X. Zhang, X. Xu, H. Chen, and Z. Xiong, "Net global warming potential and greenhouse gas intensity from the double rice system with integrated soil-crop system management: Athree-year field study," *Atmos. Environ.*, vol. 116, pp. 92–101, 2015.

[10] Y. C. Ma *et al.*, "Net global warming potential and greenhouse gas intensity of annual rice-wheat rotations with integrated soil-crop system management," *Agric. Ecosyst. Environ.*, vol. 164, pp. 209–219, 2013.

[11] I. Naroznova, J. Møller, and C. Scheutz, "Global warming potential of material fractions occurring in source-separated organic household waste treated by anaerobic digestion or incineration under different framework conditions," *Waste Manag.*, vol. 58, pp. 397–407, 2016.

[12] J. G. Owens, "Greenhouse gas emission reductions through use of a sustainable alternative to SF6," *34th Electr. Insul. Conf. EIC 2016*, no. June, pp. 535–538, 2016.

[13] T. J. Wallington, M. P. Sulbaek Andersen, and O. J. Nielsen, "Atmospheric chemistry of short-chain haloolefins: Photochemical ozone creation potentials (POCPs), global warming potentials (GWPs), and ozone depletion potentials (ODPs)," *Chemosphere*, vol. 129, pp. 135–141, 2015.

[14] M. F. Akorede, H. Hizam, M. Z. A. Ab Kadir, I. Aris, and S. D. Buba, "Mitigating the anthropogenic global warming in the electric power industry," *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 2747–2761, 2012.

[15] R. deRichter and S. Caillol, "Fighting global warming: The potential of photocatalysis against CO2, CH4, N2O, CFCs, tropospheric O3, BC and other major contributors to climate change," *J. Photochem. Photobiol. C Photochem. Rev.*, vol. 12, no. 1, pp. 1–19, 2011.

[16] R. Sundararajan, "Long term acid rain multistress performance of thermoplastic and thermoset polymeric insulators," *2010 5th Int. Conf. Ind. Inf. Syst. ICIIS 2010*, pp. 544–549, 2010.

[17] Z. Dong, Y. Qin, Y. Yang, D. Zhou, X. Xu, and J. Qiu, "Effect of RE3+electronegativities on luminescence property of Ba5Si8O21:Eu2+persistent phosphor," *J. Rare Earths*, vol. 34, no. 5, pp. 453–457, 2016.

[18] K. Li, X. Wang, and D. Xue, "Electronegativities of elements in covalent crystals.," *J. Phys. Chem. A*, vol. 112, no. 34, pp. 7894–7, Aug. 2008.

[19] J. Furtado, F. De Proft, and P. Geerlings, "The noble gases: how their electronegativity and hardness determines their chemistry.," *J. Phys. Chem. A*, vol. 119, no. 8, pp. 1339–46, Feb. 2015.

[20] L. R. Murphy, T. L. Meek, A. L. Allred, and L. C. Allen, "Evaluation and Test of Pauling's Electronegativity Scale," *J. Phys. Chem. A*, vol. 104, no. 24, pp. 5867–5871, 2000.

[21] Z. Peng, M. Hu, Z. Yuan, T. Feifei, and L. Zhiliang, "Atomic Electronegativity Interaction Vector and Atomic Hybrid State Index Utilized for Spectroscopic Simulation of 13 C Nuclear Magnetic Resonance of Amino Acids," vol. 34, no. 2, 2006.

[22] A. L. Allred, "Chats de Schrödinger du champ et étude de la décohérence," vol. 17, no. 1949, pp. 215–221, 1961.

[23] R. R. Reddy *et al.*, "Correlation between optical electronegativity and refractive index of ternary chalcopyrites, semiconductors, insulators, oxides and alkali halides," *Opt. Mater. (Amst).*, vol. 31, no. 2, pp. 209–212, Oct. 2008.

[24] H. Zhang, J. Wu, and P. Lu, "A study of the radiative forcing and global warming potentials of hydrofluorocarbons," *J. Quant. Spectrosc. Radiat. Transf.*, vol. 112, no. 2, pp. 220–229, Jan. 2011.

[25] M. S. Kamarudin, "A survey on the potential of CF 3 I gas as an alternative for SF 6 in high voltage applications," no. September, 2010.

[26] K. Hayashi, A. Nakagawa, N. Itsubo, and A. Inaba, "Expanded damage function of stratospheric ozone depletion to cover major endpoints regarding life cycle impact assessment," *Int. J. Life Cycle Assess.*, vol. 11, no. 3, pp. 150–161, 2006.

[27] K. S. Kumar and K. Rajagopal, "Computational and experimental investigation of low ODP and low GWP HCFC-123 and HC-290 refrigerant mixture alternate to CFC-12," *Energy Convers. Manag.*, vol. 48, no. 12, pp. 3053–3062, 2007.

[28] T. Juliandhy, T. Haryono, Suharyanto, and I. Perdana, "Breakdown Voltage of CF3CHCl2gas an Alternative to SF6Gas using HV Test and Bonding Energy Methods," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 336, no. 1, p. 12004, 2018.

[29] T. Juliandhy, T. Haryono, Suharyanto, and I. Perdana, "Comparison of CF3CHCl2 Gas with SF6 Gas as an Alternative Substitute for Gas Insulated Switchgear Equipment," in *2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, 2017, no. December, pp. 198–203.

[30] K. K. Pandey and P. Patidar, "Structure and bonding energy calculations of nitrosyl, thionitrosyl and selenonitrosyl complexes [(PNP)Ir(NX)]+ (X=O, S, Se): A DFT study," *Polyhedron*, vol. 68, pp. 87–93, Jan. 2014.

[31] T. H. etal Tedy Juliandhy, "Effect of Flue Gas Desulphur failure on Isolator Flashover in Tanjung Jati B Jepara Substation," Universitas Gadjah Mada., 2014.

[32] T. Juliandhy, T. Haryono, Suharyanto, and I. Perdana, "Breakdown voltage for mixed CF3CHCl2+N2gases as gas insulation application," *2018 Int. Conf. Inf. Commun. Technol. ICOIACT 2018*, vol. 2018–Janua, no. April, pp. 833–837, 2018.

[33] T. Juliandhy, T. Haryono, Suharyanto, and I. Perdana, "Investigation of the Reliability of CF3CHC12+ N2 Gas Mixture as a Potential Substitute for SF6," *2018 4th Int. Conf. Sci. Technol.*, pp. 1–4, 2018.

[34] Q. Li, Y. Zhang, and G. Hu, "Techno-economic analysis of advanced biofuel production based on bio-oil gasification," *Bioresour. Technol.*, vol. 191, pp. 88–96, 2015.

[35] A. Buttler, R. Koltun, R. Wolf, and H. Spliethoff, "A detailed techno-economic analysis of heat integration in high temperature

electrolysis for efficient hydrogen production," *Int. J. Hydrogen Energy*, vol. 40, no. 1, pp. 38–50, 2015.

[36] T. Kuramochi, A. Ramírez, W. Turkenburg, and A. Faaij, "Techno-economic prospects for CO2 capture from distributed energy systems," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 328–347, Mar. 2013.

[37] Q. Li and G. Hu, "Techno-economic analysis of biofuel production considering logistic configurations," *Bioresour. Technol.*, vol. 206, pp. 195–203, 2016.