Breakdown Voltage of CF₃CHCl₂ gas an Alternative to SF₆ Gas using HV Test and Bonding Energy Methods

Tedy Juliandhy¹*, T. Haryono¹, Suharyanto¹, Indra Perdana²

¹Departement of Electrical Engineering and Information Technology,  
²Departement of Chemical Engineering, Engineering Faculty, GadjahMada University

* tedy.s3te14@mail.ugm.ac.id

Abstract. For more than two decades of Sulphur Hexafluoride (SF₆) gases is used as a gas insulation in high voltage equipment especially in substations. In addition to getting an advantage as an insulating gas. SF₆ gas is recognized as one of the greenhouse effect gases that cause global warming. Under the Kyoto Protocol, SF₆ gas is one of those gases whose use is restricted and gradually reduced to the presence of a replacement gas for SF₆ gas. One of the alternative gas alternatives which have the potential of replacing SF₆ gas as an insulating gas in Gas Insulated Switchgear (GIS) equipment in the substation is Dichlorotrifluoroethane (CF₃CHCl₂) gas. The purpose of this paper is to enable a comparison of breakdown voltage with high voltage test and method of calculating Bonding energy to Dichlorotrifluoroethane gas as substitute gas for SF₆ gas. At 0.1 bar gas pressure obtained an average breakdown voltage of 18.68 kV / mm at 25°C chamber temperature and has the highest breakdown voltage at 50°C with a breakdown voltage of 19.56 kV / mm. The CF₃CHCl₂ gas has great potential as an insulating gas because it has more insulation ability high of SF₆ gas, and is part of the gas recommended under the Kyoto Protocol. Gas CF₃CHCl₂ has the capacity to double the value of electronegativity greater than SF₆ gas as a major requirement of gas isolation and has a value of Global Warming Potential (GWP) and Ozone Depleting lower than from SF₆ gas.

1. Introduction

Gas Insulated Switchgear (GIS) on high voltage equipment is grounded by the power system and the transmission system is expected to function reliably and efficiently[1]–[3]. The ability of gas insulation in GIS equipment plays an important role in performing this function. SF₆ gas insulation assists the reliability of the system with its ability to isolate the gas and as an electric arc extinguisher during switching.

GIS is an electrical substation that uses SF₆ gas as its insulating medium. SF₆ gas in addition to its advantages as a gas insulation used in high voltage equipment also has a deficiency as a gas that is limited or reduced its use in Kyoto Protocol conventions because it causes environmental damage such as greenhouse effect, global warming and the occurrence of acid rain in certain areas. One of the contents of the amendment of the Kyoto Protocol is the utilization of alternative gas alternatives as a more environmentally friendly gas insulation[4]–[9]. Under the Kyoto Protocol, the use of SF₆ gas as an insulating medium for high voltage electrical appliances and other applications is recommended for restriction and ultimately terminated until the discovery of a replacement gas that does not pollute the environment and damage the environment. A large amount of research and research investigating new gases as an alternative SF₆ gas as gas insulation in substation equipment shows a positive response to
the Kyoto Protocol Convention[10]. The response form of the researchers can be seen in the number of researchers who explored the substitute gas of SF\(_6\) gas at most and by mixing the SF\(_6\) gas with other gases.

Monitoring and maintenance of the quality of gas insulation are essential to ensure reliable operation of electrical appliances. In addition to having a reliable capability as a gas insulation, SF\(_6\) is also the largest contributor to environmental damage with global warming, greenhouse effect, and acid rain. Global warming and acid rain are one of the causes of environmental damage caused by SF\(_6\) gas usage[11]–[14]. A more serious characteristic of damage is the formation of acid rain, caused by chemical reactions in the air during leakage of high voltage equipment installation using SF\(_6\) gas as an insulating medium.

The issue of global warming and the depletion of the ozone layer at Kyoto's climate convention resulted in the Kyoto Protocol as a basis for restrictions on the use of gases that contribute to global warming and environmental degradation. It cannot be ignored that the utilization of SF\(_6\) gas in High Voltage equipment especially in a substation of Gas Insulated Switchgear (GIS) equipment is not separated from SF\(_6\) capability as proven gas isolation. The ability of SF\(_6\) as gas insulation because it has the ability to extinguish the electric arc when switching on high equipment also has the value of isolation (dielectric strength) of 90 kV / mm bar. This capability is used on SF\(_6\) gas at the base of gas utilization SF\(_6\) Gas Insulated Switchgear (GIS). The specification of SF\(_6\) gas so that it is used as gas insulation in high voltage equipment can be seen in the table below / Table I:

| Specifications       | Sulphur hexafluoride (SF\(_6\)) |
|----------------------|---------------------------------|
| Breakdown Voltage    | 90 kV/mm                        |
| Electronegativity    | 3.98                            |
| Relative Dielectric Strength | 2.5                      |
| GWP                  | 23900                           |
| ODP                  | 0.08                            |
| Atmosphere live-time | 3200 Year                       |

In table 1, the outline of SF\(_6\) gas has good isolation capability in high voltage equipment usage, its ability to withstand breakdown voltage, its electronegativity, and its insulating strength value compared to O\(_2\) gas. As for the eco-friendly gas requirements required by the Kyoto Protocol, SF\(_6\) gases including environmentally damaging gas are seen at a value of Global Warming Potential (GWP) of 23900 times compared to CO gas, depleting the ozone layer or Ozone Depleting Potential (ODP) of 0.08, and the residence time in the atmosphere reaches 3200 years (Atmosphere Live Time value)[15]–[18]. The existence of the Kyoto Protocol was positively responded by the researchers to develop a gas insulation study in accordance with the requirements of the Kyoto Protocol. The researcher's response to finding alternative gas as an SF\(_6\) gas replacement has been largely undertaken by the following research using either new gas or SF\(_6\) gas mixed with other gases in order to reduce the released concentrate in the air as shown in the research in Table II [19]–[22].

| Researcher/Year | Research Title                                                                 | Research methods                             |
|-----------------|--------------------------------------------------------------------------------|----------------------------------------------|
| GenyoUeta, et al (2011) | Evaluation of Breakdown Characteristics of CO\(_2\) Gas for Non-standard Lightning Impulse Waveforms Breakdown Characteristics under Single frequency Oscillation Waveforms of 1.3 MHz to 4.0 MHz | Testing CO\(_2\) gas as an alternative to SF\(_6\) gas with Non-standard Lightning Impulse Waveforms |
| Junichi Wada, et al (2013) | Evaluation of Breakdown Characteristics of N\(_2\) Gas for Non-standard Lightning Impulse | Testing N\(_2\) gas as an alternative to SF\(_6\) gas with |
One of the potential gases used as an alternative to SF6 gas is CF3CHCl2 (Dichlorotrifluoroethane) gas. Use of CF3CHCl2 gas as an alternative gas and has great potential to replace SF6 gas because CF3CHCl2 gas has properties and characteristics similar to SF6 but in accordance with the insulation gas as required by the Kyoto Protocol. Characteristics of dichlorotrifluoroethane gas that has almost the same characteristics as in the forming elements bonding compounds. If the SF6 gas has the element F (Flour) as an electronegative element and belongs to the halogen group in the chemical element CF3CHCl2 gas has elements F and Cl as elements that are electronegative. Because of its specific electronegative properties, the CF3CHCl2 gas also has the ability to extinguish the electric arc. The ability of gas insulation owned by SF6 gas is related to chemical bond with its compounds. Theoretically, the stronger the chemical compound bond, the greater the energy required to release the bonds of the compound. The energy required to release the bonding chemical compounds in the electrical world is referred to as the breakdown voltage. Translucent voltage is a voltage that can penetrate chemical bonds on compounds that are given the minimum voltage or tension required to decompose or release bonds to a chemical compound. In bond chemistry in an interconnected molecule is called binding energy. The binding energy itself is defined as the energy required to release the bond between the forming atoms in the molecule of a compound. Considering the characteristics and capabilities of CF3CHCl2 gas as a substitute for SF6 alternative gas the authors will try to compare the capability of CF3CHCl2 gas by using High Voltage (HV) test and binding energy calculation method to get the estimation or prediction of the penetration value of the material used as the insulator.

In this paper, we discussed the comparison of CF3CHCl2 gas breakdown voltage by using high voltage test and penetrating voltage value by calculation or prediction of binding energy calculation. If the penetrating voltage value of the binding energy can be used as a prediction to determine the penetrating voltage value of a substance, this method can be recommended as a way to predict the penetrating voltage value of a compound to obtain the insulating material.

2. Experimental setup

2.1. High Voltage test and model

Testing using high voltage using equipment: Vacuum Pump brand Value, Testing transformer type JEC-120 with primary voltage 100-200 AC and secondary voltage 100 kV AC. A test tube gas chamber with a diameter of 30cm and a length of the 40cm tube as showed in figure1 and figure 2.
While the series of test equipment shown in Figure 2

![Figure 2. Circuit of HV Test](image)

Before the test, any gas inside the chamber tube is emptied using a vacuum pump. After the chamber tube is empty or vacuum condition then continued by filling the chamber with test gas / CF$_3$CHCl$_2$. Gas pressure is included in the chamber at 0.1 bar pressure, electrode gap set at 1mm and 2mm gap distances, the temperature in the chamber set at 25°C, 30°C, 40°C, and 50°C. Increased temperature in the chamber using 100-watt heaters and controller with a thermocouple. After the initial treatment is carried out according to the setting, the CF$_3$CHCl$_2$ gas test is conducted to determine the penetrating voltage value of the CF$_3$CHCl$_2$ gas material when applied. For each test, sampling test of the breakdown voltage is 5 times. From the results of the 5-time test taken the average value of the test gas voltage in kV / mm Bar. The result of this mean breakdown value will be compared with the value of the penetrating voltage that can be obtained from the prediction method of the energy value of the bond and the value of the voltage required to achieve the penetrating voltage value in the test gas material. Table III shows the breakdown voltage of high voltage test results.

| P (Bar) | d (mm) | T (Celsius) | **Breakdown Voltage (kV)** | **Average (kV)** |
|---------|--------|-------------|----------------------------|-----------------|
| 0.1     | 1      | 25          | 19.4 18.2 19.5 17.9 18.4   | 18.68           |
| 0.1     | 1      | 30          | 19.4 17.9 17    16.6 16.3   | 17.44           |
| 0.1     | 1      | 40          | 16.7 16.7 17.7 16.3 16.5   | 16.76           |
| 0.1     | 1      | 50          | 19.6 18.2 20.9 20.5 18.6   | 19.56           |
| 0.1     | 2      | 25          | 37.3 37.3 38.4 34.3 34.9   | 36.44           |
2.2. Bond Energy

Bond energy is the energy needed to break the bonds between atoms in a molecule. The SI unit of bond energy is kilojoules per mole. The greater the binding energy in a compound the greater the energy required to release the binding of the compound. The following table shows the binding energy of the various bonds that have been recorded in the binding energy of a compound/Table IV:

| 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                  |

Comparison bonding energy calculation on SF₆ gas and CF₃CHCl₂ gas below is obtained the value of binding energy equal to:

Using the binding energy table in accordance with table 3 was obtained:

\[
\text{SF}_6 \longrightarrow S + 6\text{F} \quad (1)
\]

\[
\text{S-F} = (6 \times 327) = 1962 \text{ kJ/mol} \quad (2)
\]

The binding energy of the chemical reaction of SF₆ is 1962 kJoule/mol. Dichlorotrifluoroethane (CF₃CHCl₂) gas binding energy. Using the binding energy table in accordance using Table IV was obtained:

\[
\begin{align*}
\text{F} & \rightarrow \text{Cl} \\
\end{align*}
\]
The binding energy of the chemical reaction of CF₃CHCl₂ is:

\[
\begin{align*}
3 ( \text{C—F} ) &= 3 ( 485 \text{kJ/mol} ) = 1455 \text{kJ/mol} \\
2 ( \text{C—Cl} ) &= 2 ( 328 \text{kJ/mol} ) = 656 \text{kJ/mol} \\
\text{C—H} &= 1 ( 413 \text{kJ/mol} ) = 413 \text{kJ/mol}
\end{align*}
\]

Bond Energy CF₃CHCl₂ = ( 1455 + 656 +413 ) kJ/mol = 2524 kJ/mol.

3. Result and Discussion

High voltage tests the value of gas penetration voltage CF₃CHCl₂ after testing 5 times obtained the value of translucent voltage average 18.68 kV/mm or 186.6 kV/mm bar in temperature condition 25°C. While the average value of test breakdown voltage of the test gas at a temperature of 50°C obtained value 19.56 kV/mm or 195.6 kV/mm bar. As the temperature is increased then the gas in the chamber space will undergo development so as to increase the density of the test gas in the chamber. Due to the gas that expands in the chamber, there steps up the pressure, and the greater the pressure in the chamber the test gas bond will be compressed in other words the stronger the bonding of the molecule in the chemical compound. The stronger the chemical bond, the greater the energy needed to release the chemical bonds on the compound forming or the greater the bonding energy, the greater the ability of the test gas to withstand the penetration voltage/insulation properties the greater. The percentage increase in the capability of the gas holds a breakdown voltage of 4.5% so that at 50°C for the capability of the gas in holding the penetrating voltage inside the chamber is higher than the CF₃CHCl₂ gas capability at 25°C. When the chamber was given a temperature condition at 30°C - 40°C the CF₃CHCl₂ gas capability suppressed a translucent voltage ranging from 16-17 kV. The value of the translucent voltage used as a reference then took the lowest penetration value of 16.76 kV/mm or 167.6 kV/mm bar at a temperature of 40°C. GIS equipment at the substation using 7 bar pressures in operation on SF6 gas has a 90 kV/mm bar capabilities. If the CF₃CHCl₂ gas is used in the distended state with a 7 bar chamber pressure such as the treatment of SF₆ gas, the gas capacity of CF₃CHCl₂ as a gas isolation can withstand a penetrating voltage of 167.6 kV/mm Bar multiplied by the amount of gas in chamber (7 Bar) obtaining a penetration voltage value of 1173.2 kV whereas the ability of SF₆ gas to withstand a breakdown voltage of 90 kV/mm Bar multiplied by the amount of gas entered into the chamber (7 Bar) gets a breakdown voltage of 630 kV. The percentage of incremental voltage gain that can be achieved by CF₃CHCl₂ gas is 86%.

By using the binding energy method, SF₆ gas binding energy of 1962 kJoule/mol, while the bonding energy for CF₃CHCl₂ gas is 2524 kJoule/mol. In accordance with the description above the size of the binding energy affects the ability of the gas to withstand breakdown voltage. The greater the binding energy possessed by a compound the greater the compound's ability to withstand breakdown voltage or to become more insulating. If the binding energy of 1962 kJoule/mol, an SF6 gas capable of withstanding voltage of 630 kV at 7 Bar chamber pressure, the ability of CF₃CHCl₂ gas breakdown voltage which has 2524 kJoule/mol is achieved at 1173.2 kV. The ability of SF₆ gas breakdown voltage with the same code in the chamber with 7 Bar pressure is obtained a breakdown voltage of 810 kV.

In the above description and explanation of those two methods (HV test method and bonding energy calculation method) can be performed with the comparative value of breakdown voltage on CF₃CHCl₂ gas. By testing the high voltage gas CF₃CHCl₂ has a total penetration value at 7 bar pressures of 1173.2 kV, while the value of breakdown voltage on CF₃CHCl₂ gas by using the binding energy method obtained the value of 8-10 kV penetrating voltage. Utilizing the HV test the breakdown voltage obtained at CF₃CHCl₂ gas has 363.2 kV differences greater than the binding energy method.
Comparison of CF$_3$CHCl$_2$ gas through voltage test value by HV test method compared with penetrating voltage value of binding energy method obtained CF$_3$CHCl$_2$ gas capability can withstand 1.45 times penetration voltage greater than penetrating voltage with binding energy method.

4. Conclusion

Based on the description, results and discussion on the comparison of CF$_3$CHCl$_2$ gas breakdown voltage using HV test and binding energy method can be concluded:

- Gas CF$_3$CHCl$_2$ is very feasible to be used as a gas substitute for gas insulation on SF6 gas in substations because it has a similar specification with SF6 gas.
- Gas CF$_3$CHCl$_2$ has the ability as an electric arc extinguisher when there is switching on high voltage equipment because it contains compound F (Fluor) and Cl (Chlor) which is halogen class and electronegative is the ability of the gas to extinguish the electric arc.
- The result of high voltage test of gas CF$_3$CHCl$_2$ able to withstand breakdown voltage above SF6 gas capability (SF6 gas through voltage 630 kV and gas CF$_3$CHCl$_2$ equal to 1173.2 kV).
- Comparison of CF$_3$CHCl$_2$ gas breakdown voltage by using high voltage testing method and bonding energy method obtained a higher yield from SF6 gas breakdown voltage (HV test method 1173.2 kV and using bonding energy method of 810 kV).
- Gas penetration value of CF$_3$CHCl$_2$ with HV test method compared to the bonding energy method obtained by the difference of greater penetration voltage 363.2 kV and CF$_3$CHCl$_2$ gas breakdown ratio of 1.45 times the binding energy method.

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