Electric Field and Current Density Performance Analysis of \( \text{SF}_6 \), \( \text{C}_4\text{F}_8 \) And \( \text{CO}_2 \) Gases As An Insulation

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Abstract. \( \text{SF}_6 \) gases are not only widely used as an insulating component in electric power industry but also an arc extinguishing performance in high voltage (HV) gas-insulated circuit breaker (GCB). \( \text{SF}_6 \) gases is generally used in the production of semiconductor materials and devices. Though these gases is widely used in many application, the presences of temperature hotspot in the insulations may affect the insulation characteristics particularly electric field and current density. Therefore, it is important to determine the relationship between electric field and current density of gases used in the insulator in the presence of hotspot. In this paper, three types of gases in particular Sulphur Hexafluoride (\( \text{SF}_6 \)), Octafluorocyclobutane (\( \text{C}_4\text{F}_8 \)), and Carbon Dioxide (\( \text{CO}_2 \)) was used in the insulator for gas insulation with the presence of two hotspots. These two hotspots were detected by referring the rising temperature in the insulator which are 1000 and 2000 Kelvin temperature for hotspot 1 and hotspot 2, respectively. From the simulation results, it can be concluded that Sulphur Hexafluoride (\( \text{SF}_6 \)) is the best choice for gas insulation since it had the lowest current density and electric field compared to Octafluorocyclobutane (\( \text{C}_4\text{F}_8 \)), and Carbon Dioxide (\( \text{CO}_2 \)). It is observed that the maximum current density and electric field for \( \text{SF}_6 \) during normal condition are 358.94 x 10^3 V/m and 0.643 x 10^9 A/m^2, respectively. Meanwhile, during temperature rising at hotspot 1 and hotspot 2, \( \text{SF}_6 \) also had lowest current density and electric field compared to the other gases where the results for \( E_{\text{max}} \) and \( J_{\text{max}} \) at hotspot 1 are 322.34 x 10^3 V/m and 1.934 x 10^9 A/m^2, respectively; While, \( E_{\text{max}} \) and \( J_{\text{max}} \) at hotspot 2 are 259.77 x 10^3 V/m and 2.824 x 10^9 A/m^2. The results of this analysis can be used to find the best choices of gas that can be used in the insulator.

1. Introduction

Dielectric gasses are utilized as electrical covers as a part of high voltage applications, such as transformer, circuit breakers, switchgear and etc. The gas that most commonly used are Sulphur Hexafluoride (\( \text{SF}_6 \)), Octafluorocyclobutane (\( \text{C}_4\text{F}_8 \)), Carbon Dioxide (\( \text{CO}_2 \)) and etc. \( \text{SF}_6 \) is widely use during the extinction phase for arc quenching and also gas insulating in high voltage (HV) gas circuit breaker (GCB). Furthermore, \( \text{C}_4\text{F}_8 \) is an organofluorine compound which enjoys several niche applications. It is related to cyclobutane by replacement of all C-H bonds with C-F bonds. Application that usually use with the gases is a production
of semiconductor materials and devices. Octafluorocyclobutane (C₄F₈) serves as a deposition gas and etchant [1]. CO₂ is an odorless and colorless vital in earth. It present in the atmosphere and formed during respiration.

Electric field is a component of the electromagnetic field. It is a vector field and is generated by electric charges or time-varying magnetic fields, as described by Maxwell’s equations [2]. To design an electrical equipment, current density is most important which is need to be emphasized. The circuit performance is fully depends on the designed current level. Current density also an important parameter in Ampere’s Circuital Law which is relates current density to magnetic field [3].

Therefore this paper presents the electric field and current density performance of three gasses in particular Sulphur Hexafluoride (SF₆), Octafluorocyclobutane (C₄F₈), and Carbon Dioxide (CO₂).

2. Methodology
This paper simulates the dielectric gasses configuration effect on electric field and current density according to electrical conductivity and temperature. Quickfield Software Version 6.1 was used to simulate the electric field and current density between different characteristic of dielectric gasses which is Sulphur Hexafluoride (SF₆), Octafluorocyclobutane (C₄F₈), and Carbon Dioxide (CO₂).

It is important highlighting that the information and properties about dielectric gasses need to be studied and thoroughly investigate the advantages, disadvantages, physical properties of gasses, conductivity of gasses, and temperature of gasses in order to keep developing and design the insulator modeling without error.

Figure 1 shows the flowchart of Quickfield analysis of HVDC configuration for the overall process. The flowchart shows all the steps involving during the simulation process from creating, simulating, analyzing and solving a problem in Quickfield software.
Start

Make research about the project

Finding insulator & Identify 3 gasses for gas insulation.

Evaluation & Verification by supervisor

Yes

Create model of HVDC Insulator by using Quickfield software

Finding material properties of each design

Create each of mesh design

Solving & complete the simulation

Make analysis / simulation of normal HVDC insulator

Troubleshoot

No

Analysis OK?

Yes

Add 2 hotspot with temperature of 1000 K, 2000 K

Simulate HVDC insulator during hotspot condition

Troubleshoot

No
3. Results & Discussion

Properties of the problem that has been used for simulation on the 3 gasses are electrical conductivity, temperature, and injected voltage. Table 3.1 shows properties for the aforementioned gasses. It is worth highlighting that the insulator was injected with 33 kV with the area of hotspot 1 and hotspot 2 is same but with different temperature value.

Table 1. Properties of problem for 3 Gasses

| Properties       | Sulphur Hexafluoride (SF₆) | Octafluorocyclobutane (C₄F₈) | Carbon Dioxide (CO₂) |
|------------------|---------------------------|----------------------------|---------------------|
| Electrical Conductivity | 1.79 x 10³ S/m            | 2.98 x 10³ S/m             | 3.5 x 10³ S/m      |
| Temperature      | 318.5 Kelvin              | 388.2 Kelvin               | 304.6 Kelvin       |
| High Voltage     | 33 kV                     | 33 kV                      | 33 kV              |
| Ground           | 0 V                       | 0 V                        | 0 V                |
| Hotspot 1 :      |                           |                           |                     |
| (a) Temperature  | 1000 Kelvin               | 1000 Kelvin                | 1000 Kelvin        |
| (b) Area         | 0.0050265 m²              | 0.0050265 m²               | 0.0050265 m²       |
3.1. HVDC Insulator during Normal Condition

3.1.1. Electrical Field and Current Density of Sulphur Hexafluoride (SF$_6$).

Figure 2 shows electrical field of Sulphur Hexafluoride (SF$_6$) in normal condition. Those arrow explained direction of electric field in the insulator. Electrical field in the middle area between two electrodes had highest value in units Volt/meter. Minimum and maximum value was $192.17 \times 10^3$ V/m and $358.94 \times 10^3$ V/m.

Figure 3 shows current density of Sulphur Hexafluoride (SF$_6$) in normal condition. Current density was focused in the middle of two electrodes. Units for current density are Ampere/meter$^2$. Minimum and maximum value was $0.344 \times 10^9$ A/m$^2$ and $0.643 \times 10^9$ A/m$^2$.

3.1.2 Electrical Field and Current Density of Octafluorocyclobutane

Figure 4 shows electrical field of Octafluorocyclobutane (C$_8$F$_8$) in normal condition. Those arrow explained direction of electric field in the insulator. Electrical field in the middle area between two electrodes had highest value in units Volt/meter. Minimum and maximum value was $191.82 \times 10^3$ V/m and $366.66 \times 10^3$ V/m.

Figure 5 shows current density of Octafluorocyclobutane (C$_8$F$_8$) in normal condition. Current density was focused in the middle of two electrodes. Units for current density are Ampere/meter$^2$. Minimum and maximum value was $0.492 \times 10^9$ A/m$^2$ and $1.025 \times 10^9$ A/m$^2$. 

| Hotspot 2 : | 2000 Kelvin | 2000 Kelvin | 2000 Kelvin |
|------------|-------------|-------------|-------------|
| (a) Temperature | 0.0050265 m$^2$ | 0.0050265 m$^2$ | 0.0050265 m$^2$ |
| (b) Area | 2000 Kelvin | 2000 Kelvin | 2000 Kelvin |
3.1.3 Electrical Field and Current Density of Carbon Dioxide

Figure 6 shows electrical field of carbon dioxide (CO$_2$) in normal condition. Those arrow explained direction of electric field in the insulator. Electrical field in the middle area between two electrodes had highest value in units Volt/meter. Minimum and maximum value was $182.05 \times 10^3$ V/m and $433.10 \times 10^3$ V/m.

Figure 7 shows current density of carbon dioxide (CO$_2$) in normal condition. Current density was focused in the middle of two electrodes. Units for current density are Ampere/meter$^2$. Minimum and maximum value was $0.669 \times 10^9$ A/m$^2$ and $1.478 \times 10^9$ A/m$^2$.

3.2 HVDC Insulator on Presence of Hotspot

Hotspot is an area which had high temperature occur during gas insulation. The temperature will be rising at certain temperature. For this simulation, had two hotspot with 1000 Kelvin and 2000 Kelvin. Both hotspot had same area. Three type of gasses was simulated was made by using Quickfield with this two hotspot. Figure 8 shows two hotspot in the insulator. Hotspot 1 was on top side while hotspot 2 occur on bottom side, both were place at the middle area between two electrodes.
Figure 8: Two hotspot in the insulator

Figure 9 (a) and (b) shows properties of hotspot 1 and hotspot 2. The figure explained that temperature is rising until maximum temperature which is 1000 Kelvin for hotspot 1. Hotspot 2 showed maximum temperature is 2000 Kelvin.

3.2.1 Electrical Field and Current Density of Sulphur Hexafluoride

Figure 10 shows electrical field of Sulphur Hexafluoride ($\text{SF}_6$) in hotspot condition. Those arrow explained direction of electric field in the insulator which is from 33kV side to grounding. Those hotspot give an effect to electrical field at in the middle of two electrodes. Minimum and maximum value of electrical field for hotspot 1 were $157.82 \times 10^3$ V/m and $322.34 \times 10^3$ V/m and for hotspot 2 were $121.81 \times 10^3$ V/m and $259.77 \times 10^3$ V/m.

Figure 11 shows current density of Sulphur Hexafluoride ($\text{SF}_6$) in hotspot condition. Current density was highest at the hotspot 1 side. Minimum and maximum value of current density for hotspot 1 were $0.947 \times 10^9$ A/m$^2$ and $1.934 \times 10^9$ A/m$^2$ and for hotspot 2 were $1.326 \times 10^9$ A/m$^2$ and $2.824 \times 10^9$ A/m$^2$. 
3.2.2 Electrical Field and Current Density of Octafluorocyclobutane

Figure 12 shows electrical field of Octafluorocyclobutane (C₄F₈) in hotspot condition. Those arrow explained direction of electric field in the insulator which is from 33kV side to grounding. Those hotspot give an effect to electrical field at in the middle of two electrodes. Minimum and maximum value of electrical field for hotspot 1 were $177.86 \times 10^3$ V/m and $355.43 \times 10^3$ V/m and for hotspot 2 were $143.75 \times 10^3$ V/m and $299.61 \times 10^3$ V/m.

Figure 13 shows current density of Octafluorocyclobutane (C₄F₈) in hotspot condition. Current density was highest at the hotspot 1 side. Minimum and maximum value of current density for hotspot 1 were $1.245 \times 10^9$ A/m² and $2.488 \times 10^9$ A/m² and for hotspot 2 were $1.850 \times 10^9$ A/m² and $3.856 \times 10^9$ A/m².

3.2.3 Electrical Field and Current Density of Carbon Dioxide

Figure 14 shows electrical field of Carbon Dioxide (CO₂) in hotspot condition. Those arrow explained direction of electric field in the insulator which is from 33kV side to grounding. Those hotspot give an effect to electrical field at in the middle of two electrodes. Minimum and maximum value of electrical field for hotspot 1 were $181.10 \times 10^3$ V/m and $359.54 \times 10^3$ V/m and for hotspot 2 were $151.70 \times 10^3$ V/m and $311.10 \times 10^3$ V/m.
Figure 15 shows current density of Carbon Dioxide (CO$_2$) in hotspot condition. Current density was highest at the hotspot 1 side. Minimum and maximum value of current density for hotspot 1 were $1.399 \times 10^9$ A/m$^2$ and $2.772 \times 10^9$ A/m$^2$ and for hotspot 2 were $2.039 \times 10^9$ A/m$^2$ and $4.263 \times 10^9$ A/m$^2$.

Table 2. Comparison between electric field and current density at normal, hotspot 1 and hotspot 2 of HVDC gas insulation

| Gasses Condition | Electric Field, E (V/m) | Current Densities, J(A/m$^2$) |
|------------------|-------------------------|-------------------------------|
|                  | Minimum ($E_{\text{min}}$) | Maximum ($E_{\text{max}}$) | Minimum ($J_{\text{min}}$) | Maximum ($J_{\text{max}}$) |
| **Sulphur Hexafluoride SF$_6$** | | | | |
| Normal           | $192.17 \times 10^3$   | $358.94 \times 10^3$   | $0.344 \times 10^9$   | $0.643 \times 10^9$ |
| Hotspot 1        | $157.82 \times 10^3$   | $322.34 \times 10^3$   | $0.947 \times 10^9$   | $1.934 \times 10^9$ |
| Hotspot 2        | $121.81 \times 10^3$   | $259.77 \times 10^3$   | $1.326 \times 10^9$   | $2.824 \times 10^9$ |
| **Octafluorocyclobutane (C$_4$F$_8$)** | | | | |
| Normal           | $181.92 \times 10^3$   | $366.66 \times 10^3$   | $0.492 \times 10^9$   | $1.025 \times 10^9$ |
| Hotspot 1        | $177.86 \times 10^3$   | $355.43 \times 10^3$   | $1.245 \times 10^9$   | $2.488 \times 10^9$ |
| Hotspot 2 | 143.75 x10^3 | 299.61 x10^3 | 1.850 x10^9 | 3.856 x10^9 |
|-----------|---------------|---------------|-------------|-------------|
| Normal    | 182.05 x10^3 | 433.10 x10^3 | 0.669 x10^9 | 1.478 x10^9 |
| Hotspot 1 | 181.10 x10^3 | 359.94 x10^3 | 1.399 x10^9 | 2.772 x10^9 |
| Hotspot 2 | 151.70 x10^3 | 311.10 x10^3 | 2.039 x10^9 | 4.263 x10^9 |

| Carbon Dioxide (CO₂) |

Figure 16 shows current density against electrical field graph during normal condition. Based on the graph, carbon dioxide (CO₂) had highest value of current density and electrical field, while Sulphur Hexafluoride (SF₆) was lowest value of current density and electrical field. The data on the graph was collected from Table 4.2. The gasses can carry a current when the current density is lower. Therefore, higher electrical field in the insulator were produced high current density.

Value of current density in the hotspot 2 was smaller than in hotspot 1. Figure 17 (a) and (b) shows current density against electrical field graph during hotspot 1 and hotspot 2. Comparison from both graph was value of current density in the hotspot 2 was smaller than in hotspot 1. All the gasses in hotspot 1 had slight different value of current density. Carbon dioxide had the highest maximum current density in hotspot 1 and hotspot 2 compared to SF₆ and C₄F₈. When temperature is rising during gas insulation was affect the current density and electrical field of the gasses.

Figure 16: Current Density against Electrical Field in Normal Condition
4.0 Conclusions

The main goal of the current study was to design HVDC gas insulator and evaluate the electric field and current density in normal insulator and defect insulator. The defect insulator was analyzed by varying temperature of hotspot during insulation. Three gasses were used and compared the electrical field and current density of gas insulator. Those gasses were Sulphur Hexafluoride (SF₆), Octafluorocyclobutane (C₄F₈), and Carbon Dioxide (CO₂). Applied voltage was fixed at 33kV. Electrical field and current density of HVDC insulator were simulated using Quickfield Software.

From this research, several theories can be related to existing work. Theory part of the configurations described HVDC gas insulator configurations, the electric field, current density and effect of electric field and current density when insulator has been broken. The simulation of the HVDC gas insulator configuration is very important to evaluate the electric field and current density produced on the model. The methodology and process to get the simulation work already described in the project.

By using Quickfield software, the results has been analyzed the relationship between temperature of the hotspot occur in the insulator, maximum value of electrical field, maximum value of current density, electric field and current density pattern depends on hotspot temperature and type of gasses used in the insulator. Thus conclusion of this simulation can be identified.

Sulphur Hexafluoride (SF₆) is the best choice for gas insulation because of it had lowest current density and electric field compared to Octafluorocyclobutane (C₄F₈), and Carbon Dioxide (CO₂). $E_{\text{max}}$ and $J_{\text{max}}$ for SF₆ during normal condition are $358.94 \times 10^3$ V/m and $0.643 \times 10^9$ A/m². Furthermore, during temperature rising at hotspot 1 and hotspot 2 also had lowest current density and electric field compared to the other gasses. Results for $E_{\text{max}}$ and $J_{\text{max}}$ at hotspot 1 are $322.34 \times 10^3$ V/m and $1.934 \times 10^9$ A/m². While, $E_{\text{max}}$ and $J_{\text{max}}$ at hotspot 2 are $259.77 \times 10^3$ V/m and $2.824 \times 10^9$ A/m².

Simulation results shows that when temperature rising in certain part in the insulator, it produced lower $E_{\text{max}}$ and higher $J_{\text{max}}$ compare to normal condition. This happens because conductivity of gas in the insulator is increasing at the area of hotspot. Therefore electric field is decreasing at the area of hotspot.
Acknowledgments
The authors gratefully acknowledge the Universiti Tun Hussein Onn Malaysia, IGSP under vote U252, Power and Renewable Energy Team (PaRENT), and High Voltage Laboratory UTHM.

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