AC breakdown behavior of SF₆/N₂ gas mixtures under non-uniform field electrode configurations

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Abstract

Sulphur hexafluoride (SF₆) gas owns remarkable properties as insulation medium and current interrupter, which make it being widely used in gas-insulated equipment up to now. However, SF₆ gas has a drawback that gives adverse effect to the environment since it is a strong greenhouse gas. As the effort to minimize the SF₆ usage, this study was conducted to investigate the AC breakdown behavior of SF₆/N₂ gas mixtures with 10/90 ratio at low pressure levels (i.e. 0.11 MPa to 0.15 MPa) under non-uniform field (i.e. R0.5-plane and R6-plane electrodes configurations). The results of the study indicate that the breakdown voltage of SF₆/N₂ gas mixtures in non-uniform field increases linearly with the increase of gas pressure and electrodes gap distance. As a function of gap distance, a higher increasing rate of breakdown voltage values were achieved at lowest pressure of 0.11 MPa compared to other pressure levels. In addition, it is also found that a higher breakdown voltage values was obtained under R6-plane configuration. But, the difference in breakdown voltage values between R0.5-plane and R6-plane configuration is less significant as the gap distance is increased. It is also observed that the field efficiency factor of R6-plane is higher than R0.5-plane which indicates a more uniform field exists between the electrodes.

Keywords: AC breakdown voltage, gas insulation, non-uniform field, SF₆/N₂ gas mixtures, sulphur hexafluoride

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1. Introduction

Sulphur hexafluoride (SF₆) gas is an electronegative gas that is widely used as the primary insulator and/or arc quencher in high voltage equipment such as switchgears [1-5]. SF₆ gas also attributes colorless, non-combustible, non-toxic and thermally steady properties in its pure state. However, despite its advantages, SF₆ gas is categorized as one of the greenhouse gases thus, leads to environmental concerns [6, 7]. According to the fifth assessment report of Intergovernmental Panel on Climate Change (IPCC) in 2014, SF₆ has a global warming potentials (GWP) value of 23, 500 times greater than carbon dioxide (CO₂) over a period of 100 years [8]. Meanwhile, in the event of electrical discharges, the byproducts of SF₆ molecules are highly toxic and corrosive (e.g. S₂F₁₀ and SOF₂) [9, 10]. Until recently, various gas mixtures have been considered to replace or minimize the usage of pure SF₆ in high voltage equipment [11-17], which in line with the requirement listed in Kyoto Protocol 1997 as the effort to reduce greenhouse gas emissions [18]. One of the promising substitutes is SF₆/N₂ gas mixtures; owning to low cost, unlimited resources and remarkable synergistic effect on the dielectric characteristics [19-21]. Previous study shows that SF₆/N₂ mixtures offer appreciable breakdown properties even at low SF₆ contents [13-16]. However, most of the previous studies focused on the breakdown characteristics at high and wide range of pressure levels, i.e. up to 0.7 MPa, depending on the working pressure of gas-insulated applications. Therefore, in this study, the breakdown behavior of SF₆/N₂ gas mixtures subjected to AC stress was conducted inside a pressure vessel for various gas pressure and electrode gap distances under non-uniform field.
The focus of interest is given on the small pressure range (i.e. 0.11 MPa to 0.15 MPa) which normally used for ring main unit (RMU) switchgear application.

2. Research Method
2.1. Experimental Setup
In order to investigate the breakdown behavior of SF\textsubscript{6}/N\textsubscript{2} gas mixtures, a series of AC breakdown test was conducted inside a custom made pressure vessel [22], where the experimental setup is shown in Figure 1. The pressure vessel was designed with a volume capacity of 205 liters and the maximum withstand voltage is 70 kV/min. In this study, the test procedures of AC breakdown voltage test are complied with BS EN 60060-1 standard [23]. For the purpose of statistical analysis, a minimum of 30 consecutives breakdown data was taken for each SF\textsubscript{6}/N\textsubscript{2} gas mixtures tests. Throughout this study, the AC breakdown behavior SF\textsubscript{6}/N\textsubscript{2} gas mixtures was examined under non-uniform field for various gas pressure and electrode gap distance. The SF\textsubscript{6}/N\textsubscript{2} gas mixture ratio was fixed to 10/90, while the total gas pressure is varied at small range (i.e. 0.11 MPa to 0.15 MPa with 0.01 MPa interval). To represents different non-uniform field condition, two types of electrodes configurations were used; R0.5-plane and R6-plane configurations (refer to Figure 1). The high voltage electrodes of R0.5 and R6 have a tip radius of 0.5 mm and 6 mm, respectively, while the ground electrode of plane has a 50 mm radius. The gap distances between the high voltage and ground electrode is varied from 5 mm to 25 mm.

2.2. Experimental Method
The SF\textsubscript{6}/N\textsubscript{2} gas mixture is prepared according to Dalton’s Law as shown in (1). The equation describes that the total pressure of the gas mixture is equal to the sum of partial pressures of its individual (pure) gases [24]. For instance, at 0.10 MPa and SF\textsubscript{6}/N\textsubscript{2} (10/90) gas mixtures ratio, the partial pressure of SF\textsubscript{6} and N\textsubscript{2} is 0.01 MPa and 0.09 MPa, correspondingly. In this case, the pressure vessel was filled in with the low gas content of SF\textsubscript{6} which is 10%, followed by the other 90% of N\textsubscript{2} gas. The SF\textsubscript{6}/N\textsubscript{2} gas mixture is then left for 24 hours to ensure a uniform gas mixture before conducting the AC breakdown voltage test [13, 14].

$$P_{SF_6/N_2} = P_{SF_6} + P_{N_2}$$  \hspace{1cm} (1)

Figure 1. Experimental setup for AC voltage generations
3. Results and Analysis

3.1. AC Breakdown Voltage Distribution of SF$_6$/N$_2$ Gas Mixtures

Figure 2 shows the 3D visualization plot for mean AC breakdown voltage, $U_a$, of SF$_6$/N$_2$ gas mixtures as a function of gas pressure (i.e. 0.11 MPa to 0.15 MPa) and electrodes gap distances (i.e. 5 mm to 25 mm) under R0.5-plane and R6-plane configuration. By referring to Figure 2, the distributions of $U_a$ values at SF$_6$/N$_2$ (10/90) gas mixtures ratio is presented as the probability of breakdown event that occur at certain voltage range. According to Figure 2, the $U_a$ values of SF$_6$/N$_2$ gas mixtures under R0.5-plane and R6-plane configurations are classified into four voltage ranges (in kV); 10-20, 20-30, 30-40 and 40-50. It is noticed that both electrode configurations have the lowest $U_a$ values at 10-20 kV, while the highest $U_a$ values are at 40-50 kV. However, the distribution percentages of $U_a$ values under both electrode configurations seem different at all voltage ranges. For instance, the probability of the lowest and the highest $U_a$ values under R0.5-plane configuration are 20% and 8%, respectively. But, as R6-plane configuration is used, the probability of the lowest $U_a$ values decreases from 20% to 4%, whereas the probability of the highest $U_a$ values increases from 8% to 16%. This shows that the use of R6-plane configuration has caused more breakdown event occur at high voltage range (i.e. at 40-50 kV), which mainly due to its high electric field uniformity compared to R0.5-plane configuration.

Figure 2. 3D visualization plot for mean AC breakdown voltage of SF$_6$/N$_2$ (10/90) gas mixtures under different electrode configuration

3.2. Effect of Gap Distance to the AC Breakdown Voltage

As depicted in Figure 3, further analysis has been done on the effect of electrodes gap distance to the $U_a$ values of SF$_6$/N$_2$ gas mixtures at various gas pressures under different electrode configurations: R0.5-plane and R6 plane. It is found that the $U_a$ values increase linearly as the gap distance between the electrodes are increased from 5 mm to 25 mm. For R0.5-plane configuration, the $U_a$ values of SF$_6$/N$_2$ (10/90) mixtures at 0.11 MPa and 0.15 MPa increase by 134.7% and 99.0%, respectively, as the electrodes gap distances is varied from 5 mm to 25 mm. At the same pressure level, the increasing rates of $U_a$ values for R6-plane configuration are 78.7% and 70.3%, respectively. It can be seen that for both electrode configurations, the increasing rate of $U_a$ values decrease as the pressure are increased from 0.11 MPa to 0.15 MPa. That is to say, the effect of electrodes gap distance in affecting the $U_a$ values is more significant at 0.11 MPa. Meanwhile, as a function of pressure, it is observed that there is not much difference in $U_a$ values under R0.5-plane configuration as the pressure is increased from 0.11 MPa to 0.15 MPa, especially at 25 mm electrodes gap distance, compared to R6-plane configurations.
3.3. Effect of Gas Pressure to the AC Breakdown Voltage

Figure 4 shows the $U_a$ values of SF$_6$/N$_2$ gas mixtures as a function of pressure for two different electrode configuration; R0.5-plane and R6-plane. For a comparison purpose, this section will focus only at 10 mm and 20 mm electrodes gap distance. As one can expect, the $U_a$ values of SF$_6$/N$_2$ gas mixtures under R6-plane configuration are higher than R0.5-plane configuration for all pressure and both electrodes gap distances. However, it is found that the difference in $U_a$ values between both electrodes configurations is more significant at 10 mm gap distance for all pressure. At 0.11 MPa, the $U_a$ values differ about 33.6%. But, as the gap distance is increased to 20 mm, the effect of electrode configurations in affecting the $U_a$ values is weaken, where the difference in $U_a$ values reduce to 4.1%. From other point of view, it can be seen that the $U_a$ values under R0.5-plane configuration with 20 mm gap is almost identical to R6-plane configuration with 10 mm gap, especially when the pressure is above 0.13 MPa.

3.4. Effect of Electrode Configurations to the Electric Field Behavior

Figure 5 shows the field efficiency factor of R0.5-plane and R6-plane electrode configurations at a pressure of 0.11 MPa and various gap distances. The field efficiency factor, $\eta$ is calculated using (2), where the average electric field, $E_{\text{mean}}$ for both electrode configurations are calculated using (3), while the maximum electric field, $E_{\text{max}}$ for R0.5-plane and R6-plane configurations are calculated using (4) and (5), respectively [25]. To note, $d$ is the gap distance.
between high voltage and ground electrodes, while $r$ is the tip radius of the high voltage electrode. The $\eta$ value indicates the uniformity of electric field between the electrodes where its value lies between 0 to 1. The closer the value of $\eta$ to 1, the more uniform the electric field exists between the electrodes. Based on Figure 5, it can be seen that the value of $\eta$ under R6-plane is higher than R0.5-plane at all gap distances. Meanwhile, a decreasing pattern of $\eta$ values are observed for both electrode configurations as the gap distances are increased which suggesting a more non-uniform field exists between the electrodes.

$$\eta = \frac{E_{\text{mean}}}{E_{\text{max}}}$$

(2)

$$E_{\text{mean}} = \frac{U_a}{d}$$

(3)

$$E_{\text{max}} = \frac{2U_a}{r \ln \left( \frac{4d}{r} \right)}$$

(4)

$$E_{\text{max}} = 0.9 \frac{U_a r + d}{d} \frac{1}{r}$$

(5)

Figure 5. Field efficiency factor of SF$_6$/N$_2$ gas mixtures as a function of gap distance under different electrode configurations

4. Conclusion

In this study, a breakdown test subjected to AC voltage were conducted on the SF$_6$/N$_2$ gas mixtures for various gas mixture ratio, gas pressure, and electrode gap distance, under R0.5-plane and R6-plane electrode configurations. The amount of SF$_6$ was set to 10%, while the pressure levels were varied at small range of 0.11 MPa to 0.15 MPa. Meanwhile, the gap distances between the electrodes were set at 5 mm to 25 mm with 5 mm interval. The results show that, for both electrodes configurations, the mean AC breakdown voltage, $U_a$ of SF$_6$/N$_2$ gas mixtures increases as the pressure and electrodes gap distances are increased. It is also observed that the effect of electrodes gap distance is more significant at lowest pressure of 0.11 MPa compared to other pressure levels. Although the $U_a$ values under R6-plane configuration is higher than R0.5-plane configuration, but, the difference in $U_a$ values between these electrodes configuration is less significant as the gap distance is increased. In addition, it is found that the field efficiency factor value under R6-plane is higher than R0.5-plane configurations.

References


