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AC breakdown behavior of SF_6/N_2 gas mixtures under non-uniform field electrode configurations

N. F. Ambo[1], H. Zainuddin*[2], M. S. Kamarudin[3], J. M. Wari[4], A. Zahari[5],
[1,2,5]High Voltage Engineering Research Laboratory, Faculty of Electrical Engineering,
Universiti Teknikal Malaysia Melaka, Melaka, Malaysia, tel/ fax: +606-270 1000/+606-270 1022
[3]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia
86400 Parit Raja, Batu Pahat, Johor, Malaysia, tel/fax: +607-453 7000/+607-453 6337
[4]Indkom Engineering Sdn. Bhd. Lot 2, Asam Jawa St. 16/15, Seksyen 16,
Kawasan Perindustrian Shah Alam, 40200 Shah Alam, Selangor, Malaysia,
tel/fax: +603-5543-2388/+603-5543-2377
*Corresponding author, e-mail: hidayat@utem.edu.my

Abstract

Sulphur hexafluoride (SF_6) gas owns remarkable properties as insulation medium and current interrupter, which make it being widely used in gas-insulated equipment up to now. However, SF_6 gas has a drawback that gives adverse effect to the environment since it is a strong greenhouse gas. As the effort to minimize the SF_6 usage, this study was conducted to investigate the AC breakdown behavior of SF_6/N_2 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 SF_6/N_2 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, SF_6/N_2 gas mixtures, sulphur hexafluoride*

1. Introduction

Sulphur hexafluoride (SF_6) 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]. SF_6 gas also attributes colorless, non-combustible, non-toxic and thermally steady properties in its pure state. However, despite its advantages, SF_6 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, SF_6 has a global warming potentials (GWP) value of 23, 500 times greater than carbon dioxide (CO_2) over a period of 100 years [8]. Meanwhile, in the event of electrical discharges, the byproducts of SF_6 molecules are highly toxic and corrosive (e.g. S_2F_{10} and SOF_2) [9, 10]. Until recently, various gas mixtures have been considered to replace or minimize the usage of pure SF_6 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 SF_6/N_2 gas mixtures; owning to low cost, unlimited resources and remarkable synergistic effect on the dielectric characteristics [19-21]. Previous study shows that SF_6/N_2 mixtures offer appreciable breakdown properties even at low SF_6 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 SF_6/N_2 gas mixtures subjected to AC stress was conducted inside a pressure vessel for various gas pressure and electrode gap distances under non-uniform field.

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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_6/N_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_6/N_2 gas mixtures tests. Throughout this study, the AC breakdown behavior SF_6/N_2 gas mixtures was examined under non-uniform field for various gas pressure and electrode gap distance. The SF_6/N_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_6/N_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_6/N_2 (10/90) gas mixtures ratio, the partial pressure of SF_6 and N_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_6 which is 10%, followed by the other 90% of N_2 gas. The SF_6/N_2 gas mixture is then left for 24 hours to ensure a uniform gas mixture before conducting the AC breakdown voltage test [13, 14].

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

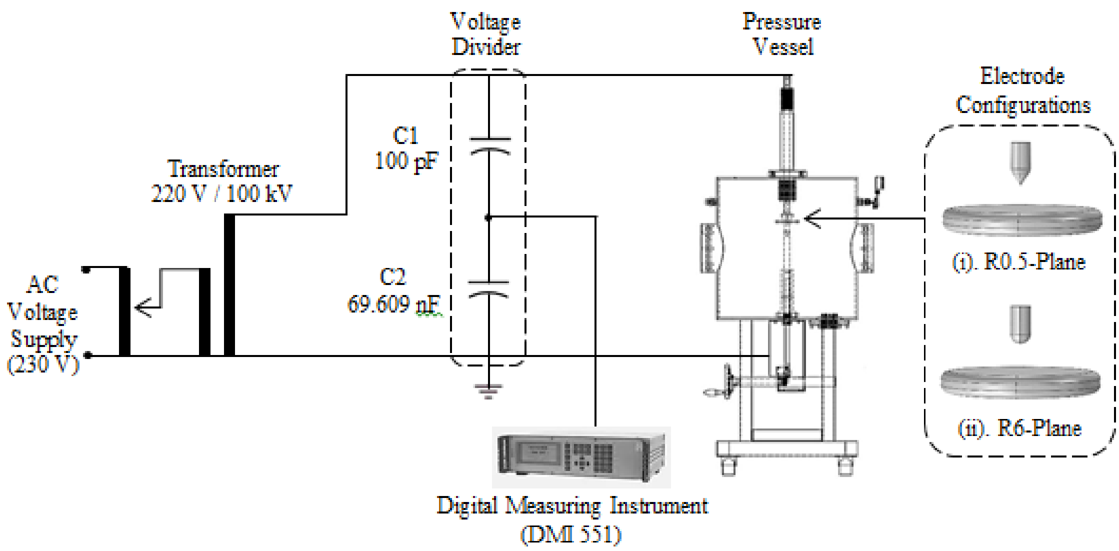
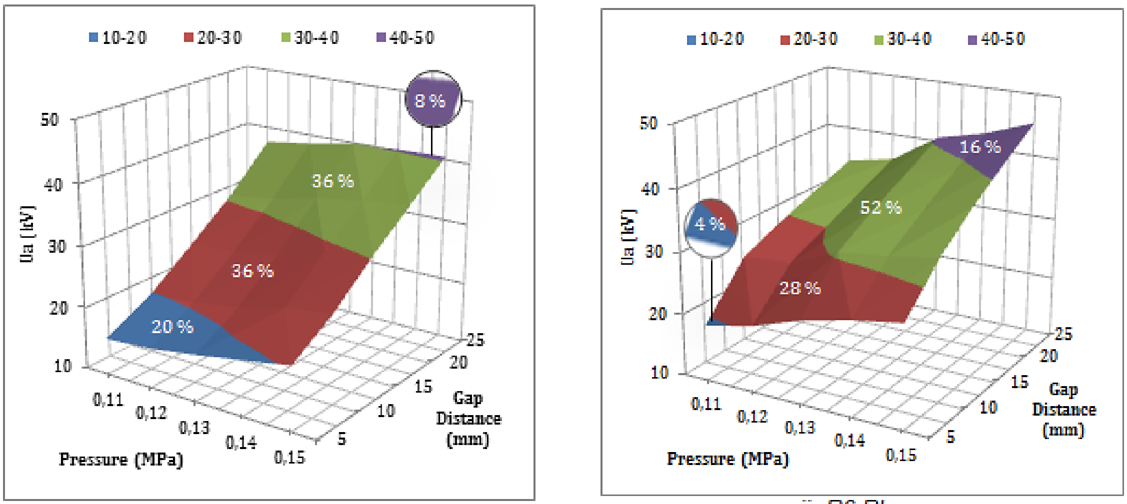


Figure 1. Experimental setup for AC voltage generations

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.



i. R0.5-Plane *ii. R6-Plane*

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.

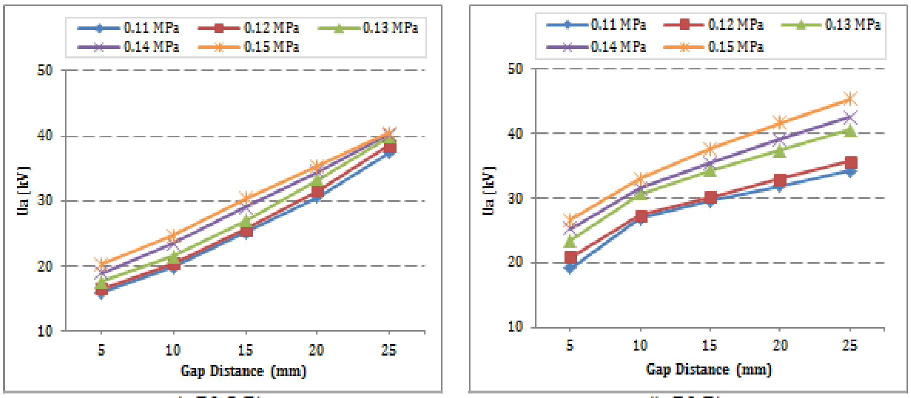


Figure 3. Mean AC breakdown voltage of SF_6/N_2 gas mixtures as a function of gap distance under different electrode configuration

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.

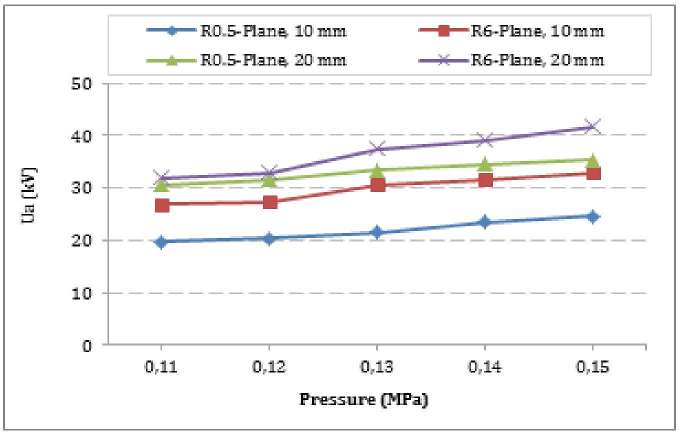


Figure 4. Comparison of AC breakdown voltage of SF_6/N_2 gas mixtures in different electrode configuration

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, η is calculated using (2), where the average electric field, E_{mean} for both electrode configurations are calculated using (3), while the maximum electric field, E_{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 η value indicates the uniformity of electric field between the electrodes where its value lies between 0 to 1. The closer the value of η to 1, the more uniform the electric field exists between the electrodes. Based on Figure 5, it can be seen that the value of η under R6-plane is higher than R0.5-plane at all gap distances. Meanwhile, a decreasing pattern of η values are observed for both electrode configurations as the gap distances are increased which suggesting a more non-uniform field exists between the electrodes.

$$\eta = \frac{E_{mean}}{E_{max}} \quad (2)$$

$$E_{mean} = \frac{U_a}{d} \quad (3)$$

$$E_{max} = \frac{2U_a}{r\,ln(\frac{4\,d}{r})} \quad (4)$$

$$E_{max} = 0.9\frac{U_a}{d}\frac{r+d}{r} \quad (5)$$

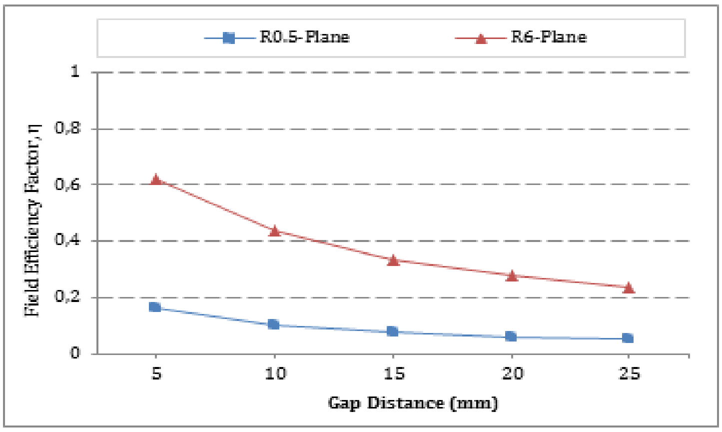


Figure 5. Field efficiency factor of SF_6/N_2 gas mixtures as a function of gap distance under different electrode configurations

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.

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