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Inception corona discharge voltages in SF_6-N_2 gas mixtures at high gas pressure

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Abstract: The use of sulphur hexafluoride (SF_6) has led to increased concentration of this gas in the atmosphere. The purpose of this work is to investigate the behaviour of SF_6-N_2 mixtures that can be considered as a potential substitute of pure SF_6. The onset corona discharge voltages have been determined from the measurements of the current-voltage characteristics under high pressures and with highly inhomogeneous fields. The results show that the onset voltages increase with the increase of the gas pressure and are relatively higher for positive polarity. It can also be seen that for low concentrations of SF_6 in the mixture the increase of the onset voltages is substantial, followed by a slow increase for elevated concentration of SF_6 in the mixture, which, can be an advantage for the substitution of SF_6.

Keywords: corona discharge, sulphur hexafuoride, insulating gas.

1. Introduction

Among electronegative gases SF_6 (sulphur-hexafluoride) has found a wide range of applications due to its superior insulating properties and chemical stability. As the size of the high voltage equipments increases the cost of insulating gas becomes appreciably high. The quantity of SF_6 released in atmosphere is therefore rising. Due to its ability to absorb and reemit IR make it a potent greenhouse gas [1-2]. With its high lifetime (more than 2000 years), it accumulates in the atmosphere and contribute to the global warming of the atmosphere, therefore SF_6 will be severely controlled in the next years. The by-products issued from decomposition of SF_6 exposed to electric discharges may be dangerous to the equipments (corrosion) and to the personnel (poisoning) [3].

These factors have stimulated the research of a replacement gas with little environmental impact. The most promising alternative is the use of gas mixtures of SF_6 with inexpensive common gases such as nitrogen (N_2). SF_6-N_2 gas mixtures have good dielectric strength, are non-toxic, non-flammable and they have a high arc quenching capacity with a good self healing ability. The purpose of this paper is to provide and discuss the measurements of the onset corona discharge voltages in SF_6-N_2 gas mixtures at higher pressure ranging from 3 to 15 bars and with different percentage of SF_6. The onset voltages were determined from the measurements of the current-voltage curves in both negative and positive polarities. A tip-plane configuration was used with the tip radius of few micro-meters and the gap between the electrodes is lower than 10 mm. Most of the data available deals with the breakdown voltages rather than the threshold voltage of corona discharge.

2. Experimental set-up

Experiments were made in a stainless-steel cell of 50 cc equipped with two quartz windows as shown in figure 1. Electrodes in a tip-to-plane configuration were mounted inside the cell. The tip electrode of few micrometers is made of tungsten and, is prepared by electrolyse technique, steel tips are also used. The gap between the electrodes varies from 5 to nearly 10 mm. The tip electrode is connected to the high D.C. voltage up to 60 kV. The stainless steel plane electrode with a radius of 12 mm is connected to an galvanometer which measures

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currents down to some microamperes. Before the cell was filled with the gas, pumping was undertaken pushing the vacuum down to nearly 3.10^{-2} Pa. The gas was introduced in the cell without prior purification. The SF_6 used in these experiments is delivered with a purity of 99.97%. The measurements were made for pressures ranging from 3 bars to 15 bars. A partial pressure method is used to mix the gases in the cell. SF_6 was first introduced followed by nitrogen. It is supposed that SF_6 and N_2 do mix quite well. The current was measured when the voltage varies upwards and downwards and after each set of measurements a resting time is observed to allow the mixture to settle down. The tip electrode is regularly changed in order to limit the radius variation due to the deposit of fluorine and sulphur. Analysis of used tips by electronic microscopy has been carried out.

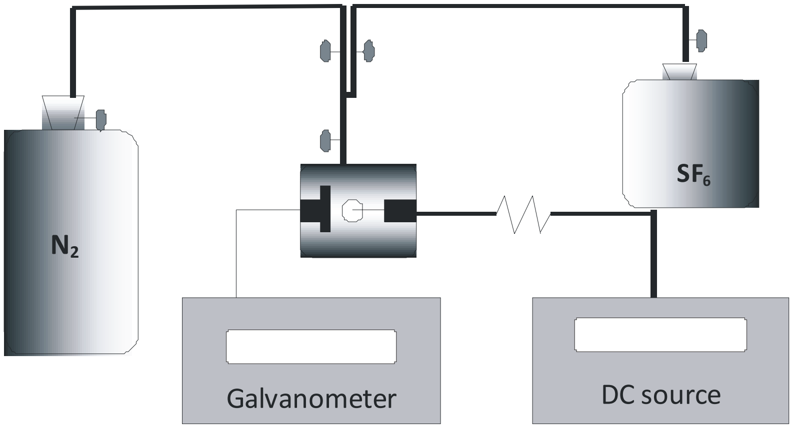


Figure 1. Experimental set-up.

3. Results and discussion

The current-voltage characteristics $I = f(V_s)$ of corona discharge in SF_6-N_2 gas mixture show that the current follows an exponential law.The measured values of corona inception voltages (V_s) as a function of the ratio of SF_6 in the mixture are shown in Figure 2 and 3 for negative and positive polarities respectively. The curves have the same tendency for both polarities and the V_s values increase with the increase of the amounts of SF_6. This behaviour may be attributed to the decrease of the net ionisation coefficient $\overline{\alpha}$ [4-5].

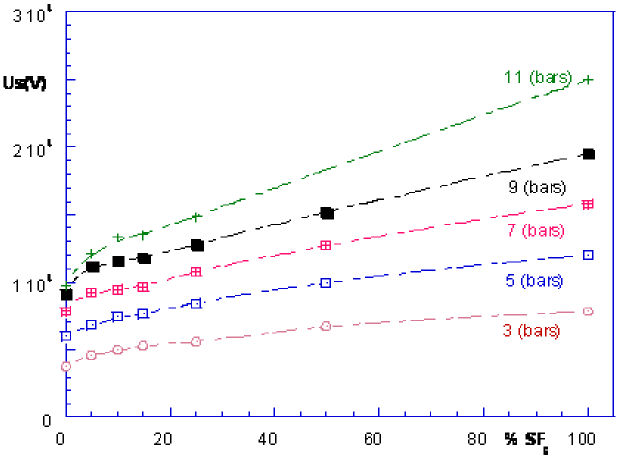


Figure 2. Curves of the onset voltages as a function of the ratio of SF_6 in the SF_6-N_2 mixture and gas pressure for negative polarity.

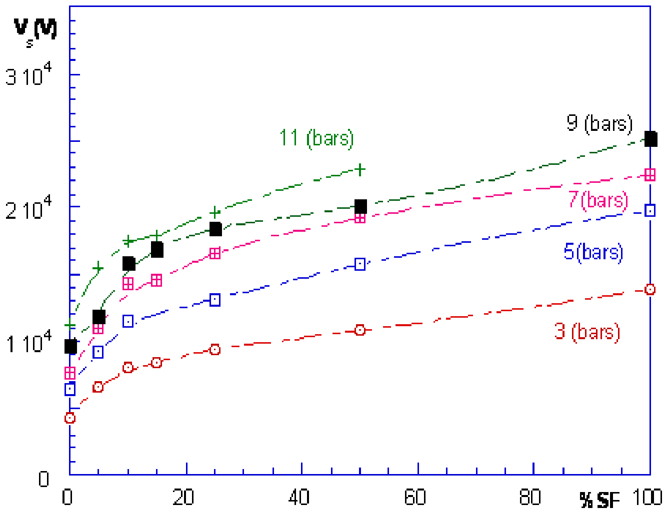


Figure 3. Curves of the onset voltages as a function of the ratio of SF_6 in the SF_6-N_2 mixture and gas pressure for positive polarity.

At higher amounts of SF_6, the onset voltages tend towards saturation. This tendency was observed in previous work [4]. The saturation may be attributed to the change of the surface of the tip electrodes. To check this assumption the surface was analysed using electronic microscopy. The analysis showed that there's some deposit on the tip after a set of electric discharge, this deposit is composed of fluorine and sulphur, but since tests are carried out with decreasing pressure such effect cannot explain saturation for higher pressures, where the tip is quite free of deposit. The saturation may be the result of the concentration of space charges, which are more active at the vicinity of the tip electrode at higher pressure [6].

It is interesting to see that a small admixture of SF_6 in the mixture provokes a sharp increase of the onset voltages of the corona discharge, which constitutes an argument for the replacement of SF_6 by SF_6-N_2 gas mixtures having very small percentage of SF_6.

Figure 4 illustrates the corona inception voltage as a function of the gas pressure for different concentrations of SF_6 in SF_6-N_2 gas mixtures for negative and positive polarities. It can be seen that the positive onset voltages are relatively higher than those of the negative polarity as found by [7-8]. This can be attributed to the mechanism of generation of initiatory electrons. Under positive polarity the main source for production of electrons is the detachment from negative ions and the difficulty for negative ions to reach the tip electrode. For negative polarity the field effect emission increases the probability of free electrons extracted from the cathode surface, which is at the highest electric field in the gap . The effect of polarity is predominant for higher amounts of SF_6 [9.]

Using the curves of figure 2 and 3, we were able to measure the working pressure for different SF_6-N_2 gas mixtures, which, can be very useful for electrical engineers. In Figure 5, are drawn the working pressure values as a function of the percentage of SF_6 for a constant onset voltage (13.8 kV) for both polarities.

In the present conditions, and for a constant onset voltage equals to 13.8 kV, a mixture of 100 % of SF_6 has a pressure equals to 3 bars for a positive polarity, whereas, for 10 % of SF_6 the pressure rises to 6.5, in order to withstand the same onset voltage. In negative polarity a mixture of 100 % of SF_6 has a pressure equals to 7.3 bars; whereas, for 10 % of SF_6 the pressure reaches 13 bars, in order to withstand the same inception voltage (13.8 kV).This result is of great interest for practical application in high voltage insulation, where GIS are used.

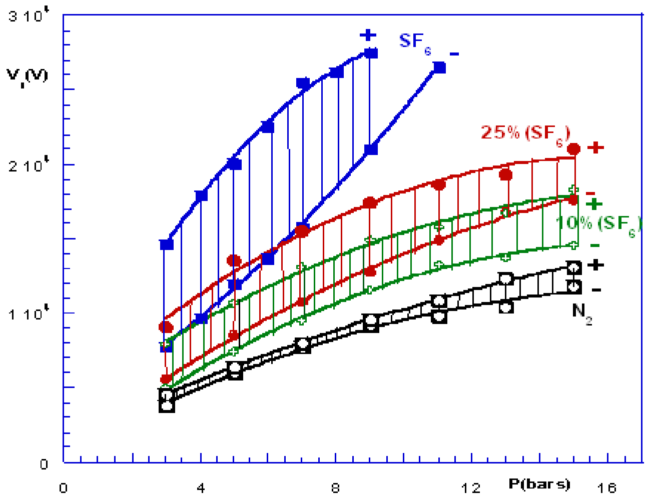


Figure 4. Corona inception voltage as a function of the gas pressure for different concentrations of SF_6 in SF_6-N_2 gas mixtures and for negative and positive polarities

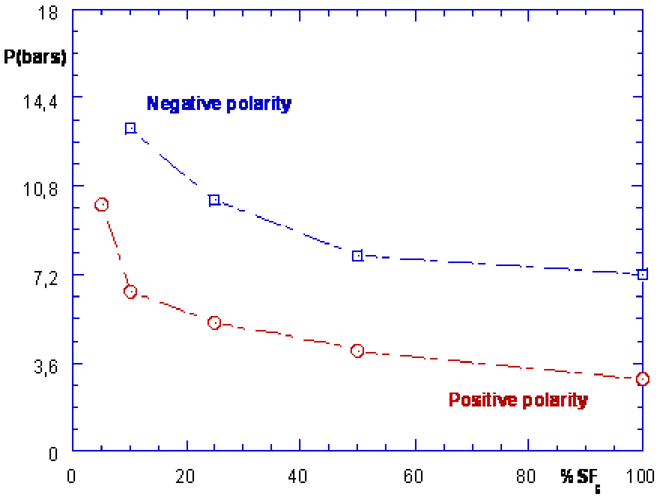


Figure 5, curves of the pressure as a function of the percentage of SF_6 for the same onset voltage (13.8 kV).

The theoretical determination of the corona inception voltage V_s is based on the expression first derived by Nitta and Shibuya [10]. The model is based on the streamer criterion as follows:

$$V\,inception = \left(\frac{E}{P}\right)_{\lim} * u * P * d * \left(1 + \frac{C}{\sqrt{P * r_p}}\right) \qquad (1)$$

Where d = gap spacing, r_p= radius of the tip electrode, P = Gas pressure.

Where u is the field utilisation factor: $u = \frac{E\,average}{E\max imum}$ (2)

The ratio of the average to the maximum electric stress, defined as the utilization factor u, is a useful criterion when comparing different electrode systems. u has been derived from the ratio of d/r_p. Figure 6 shows the dependence on gas pressure of negative inception voltage on a 10%N_2-50% SF_6 gas mixture when the electric field utilization factor is varied by changing the needle tip radius curvature from 3µm to 15µm and finally 40µm. As can be seen clearly, when the electric field nouniform coefficient is varied by changing r_p, the onset voltage characteristics are found to vary [11]. When r_p is reduced corona discharge voltage drops, this is in concordance with the values found by [12]

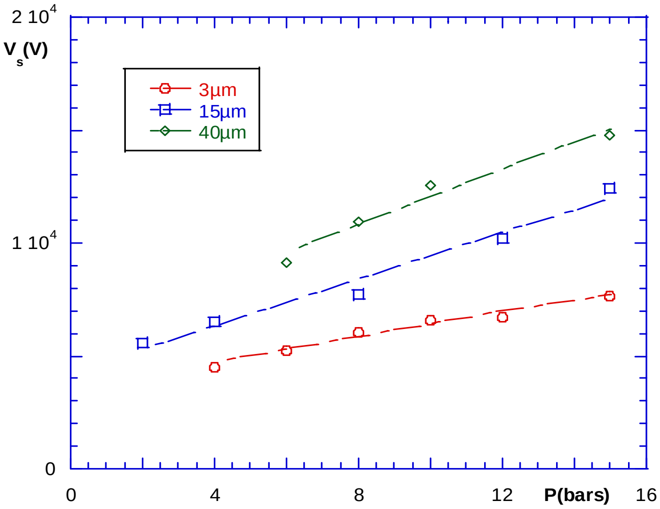


Figure 6. The dependence on gas pressure of negative inception voltage on a 10% N_2-50% SF_6 gas mixture with different values of tip radius.

The constant C in equation (1) can be determined by the following equation:

$$C = \sqrt{\frac{4K}{\beta_m * (E/P)_{\lim}}} \quad (3)$$

With K is the streamer criterion constant and β_m comes from the approximation of the net ionisation coefficient α* of the mixture: $\alpha^* = (\alpha - \eta)$, α and η are respectively the ionisation and attachment coefficients.

$$\alpha^* = \beta_m * \left[(E/P) - (E/P)_{\lim} \right] \quad (4)$$

Determination of $(E/P)_{\lim}$: It is the value of reduced field for which the equilibrium between ionisation and attachment is realised.

$$\alpha^* \left[(E/P)_{\lim} \right] = 0$$

For $(E/P) > (E/P)_{\lim}$, ionisation becomes predominant and the streamer phenomena occurs in the gap whereas, for $(E/P) < (E/P)_{\lim}$, there is no possibility to start a streamer. Malik and Qureshi [9] calculated $(E/P)_{\lim}$ for SF_6-N_2 mixtures making the assumption that:

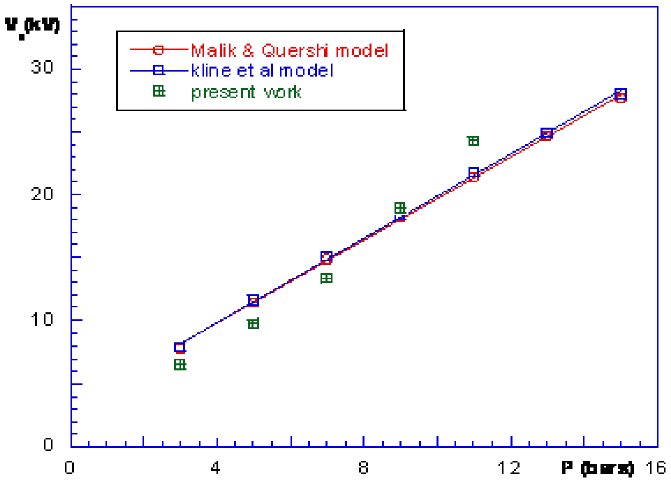
$$\left(\frac{\alpha^*}{P}\right)_{\lim} = z * \left(\frac{\alpha^*}{P}\right)_{SF_6} + (1-z) * \left(\frac{\alpha^*}{P}\right)_{N_2} \qquad (5)$$

with z = ratio of SF_6.

However, since nitrogen and SF_6 do not interact with electrons of the same range of energy, this assumption is not rigorously exact. Kline and al. [13] have shown that there's good agreement between experimental results and those calculated using the empirical expression:

$$\left(\frac{E}{N}\right)_{\lim} = \left(\frac{E}{N}\right)_{SF_6} * (\% SF_6)^{0.18}. \qquad (6)$$

In Figure 6, a comparison of the experimental results of the present work, the results found by Malik and Quershi [9] and those determined using the Kline and et.al. model[13] for pure SF_6. The models results are in good concordance with the values measured in this present work. Whereas, for a mixture of 10 % of SF_6 in the SF_6-N_2 gas mixture (Figure 7), the models overestimate the onset voltage for negative polarity. Kline's values are higher than the values determined by Malik and Quershi. The models overestimate V_s for low SF_6 ratio (10% SF_6) and are concordant for pure SF_6. The discrepancy between the models decreases with the increase of the percentage of SF_6 in the gas mixture. The experimental values of corona inception voltages (Vs) increase linearly with pressure up to 9 bars, then show deviations from the theoretical behaviour and tend to saturate. Such deviations are often attributed to surface effects, which are more sensitive at high pressure [9].



In Figure 6, a comparison of the experimental results of the present work, the results found by Malik and Quershi[9] and those determined using the Kline and et.al model [13] for pure SF_6.

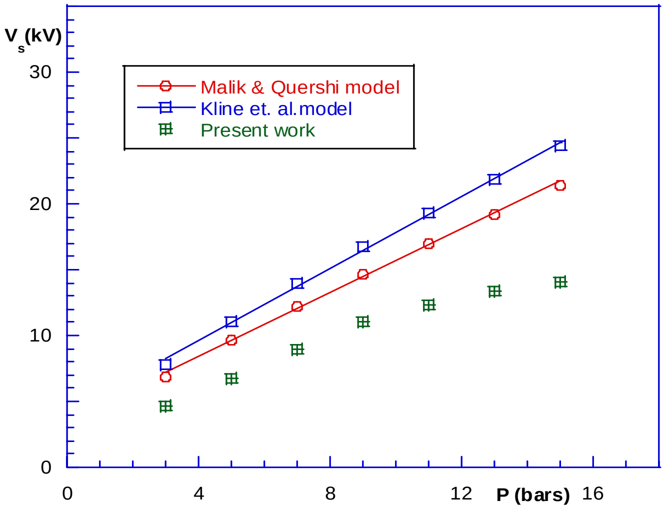


Figure 6, a comparison of the experimental results V_s(kV) of the present work, the results found by Malik and Quershi [9] and those determined using the Kline and et.al model [13] for 10% of SF_6.

4. Conclusion

The corona onset voltages V_s increase with the increase of the amounts of SF_6 but at higher pressures the measured values tend to saturate. The positive onset voltages are relatively higher, especially for high percentage of SF_6. The polarity effect is predominant for higher amounts of SF_6. For the same onset voltage a mixture with 10 % of SF_6 must works approximately at twice the pressure of pure SF_6. This is true for both polarities. The models considered in this work predict quite well the corona onset voltage for pure SF_6, whereas for SF_6-N_2 Mixtures with 10% of SF_6 they overestimate the values of the inception voltage.

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