CORONA DISCHARGE
IN SULPHUR HEXAFLUORIDE-NITROGEN GAS MIXTURE

AMAR BOUDEFEL, AHCENE LEMZADMI, ASSIA GUERROUI, ABDESSELAM BABOURI

Key words: Corona discharge, Gas dielectric, High voltage, Sulphur hexafluoride.

Experimental investigation of the current-voltage characteristics in corona discharges in SF_6-N_2 gas mixtures have been carried out in a point to plane configuration. Empirical formulae have been used to determine the corona onset voltages (V_0) in both polarities at higher pressure. The results show that for low concentrations of SF_6 the increase of the onset voltage is relatively substantial, whereas, for amounts over 10 % of SF_6 the increase is slowed down. This can be an advantage for the substitution of $SF_{6.}$ The results obtained with the empirical models are compared with the measures values. Calculated values overestimate V_0 for low SF_6 ratio (≤ 5 % SF_6) and underestimate V_0 for high pressures (≥ 50 % SF_6).

1. **INTRODUCTION**

Sulphur-hexafluoride (SF_6) is an electronegative gas, which found a wide range of applications due to its superior insulating properties and chemical stability. As the size of the high voltage equipment increases, the quantity of SF_6 released in atmosphere is therefore rising. Due to its ability to absorb and reemit infrared radiation, SF_6 is classified as a greenhouse gas and therefore, contributes to the global warming of the atmosphere [1, 2]. The by-products issued from decomposition of SF_6 exposed to electric discharges may be dangerous to the equipment (corrosion) and to the personnel (poisoning) [3]. These factors have stimulated research for 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.

Several investigations have been reported in the literature on the breakdown and corona inception behavior of SF_6 - N_2 gas mixtures [4, 5]. However, there is still insufficient information regarding the direct current corona onset voltages of such mixtures. In the present paper the corona discharge voltages have been

---

University 8 Mai 1945, Laboratoire LGEG, BP. 401, Guelma, 24000, Algeria, E-mail: boudefel99@yahoo.fr

Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **60**, *2*, p. 153–161, Bucarest, 2015

determined using the current-voltage characteristics in both negative and positive polarities. The experimental measurements were carried out at higher pressure and with highly nonuniform field. The results obtained for different amounts of SF_6 in the (SF_6-N_2) gas mixture are compared with empirical models and will be the basis for the elaboration of a useful numerical model.

2. **EXPERIMENTAL PROCEDURE**

Measurements were made in a stainless-steel cell of 50 cc equipped with two quartz windows as mentioned in [6]. Tip to plane electrodes were mounted inside the cell. The tip electrode of few micrometers is made of tungsten and is connected to the high dc voltage up to 60 kV. The gap between the electrodes varies from 5 to 10 mm. The stainless steel plane electrode with a radius of 12 mm is connected to an electrometer which, measures currents down to some microamperes. The measurements were made for pressures ranging from 3 bars to 15 bars. The current was measured when the voltage varies upwards and downwards. 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.

3. **THEORETICAL ANALYSIS**

Studies of corona discharges with point-to-plane electrode geometry started early at the end of the 9th century. Townsend derived an empirical formula for describing the current-voltage characteristics in point-to-plane corona discharges as disclosed by [7, 8]

$$I = AV\left(V - V_0\right), \tag{1}$$

where I is the corona discharge current, V the supplied voltage, V_0 the corona onset voltage and A a dimensional constant depending on the inter-electrode distance, the needle electrode radius and charge carrier mobility in the drift region and other geometrical factors. For SF_6 theoretical models to determine corona inception voltages in strongly inhomogeneous fields (tip-plane configuration) have been proposed by several authors. Nitta's [9] model is based on the streamer criterion and it is expressed in the following manner:

$$V_0 = \left(E/P\right)_{\lim} u\, P\, d \left(1 + \left(C\Big/\sqrt{P\, r_p}\right)\right), \tag{2}$$

where u is the field utilisation factor; $u = E_{\text{average}}\big/E_{\max}$.

E is the electric field, P is the gas pressure and d is the distance between the electrodes. In the case of tip-plane configuration u can be calculated using the formula given by [10]:

$$u = r_p \frac{\ln\left(1+\left(2d/r_p\right)\right)}{2d}. \tag{3}$$

In our condition, with $r_p = 50$ μm and $d = 7.25$ mm, u is of the order of 2.10^{-2}. The constant C in equation (2) can be determined by the following equation:

$$C = \sqrt{\frac{4K}{\beta_m \left(E/P\right)_{\lim}}}. \tag{4}$$

K is the streamer criterion constant and β_m comes from the approximation of the effective ionisation coefficient $\overline{\alpha}$ of the mixture [10]:

$$\overline{\alpha}/P = \beta_m \left[\left(E/P\right) - \left(E/P\right)_{\lim}\right]. \tag{5}$$

The prediction of the limiting reduced field $(E/P)_{\lim}$ at which the effective ionization coefficient over the pressure of the mixture $\left(\overline{\alpha}/P\right)_{\lim} = 0$ is given by Malik and Qureshi [11] for SF_6-N_2 mixtures by making the following assumption:

$$\left(\overline{\alpha}/P\right)_{\lim} = z\left(\overline{\alpha}/P\right)_{SF_6} + (1-z)\left(\overline{\alpha}/P\right)_{N_2}, \tag{6}$$

with z = the partial pressure 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 et al. [12] have shown that there's good agreement between experimental results and those calculated using the empirical expression eq. (7):

$$\left(E/P\right)_{\lim} = \left(E/P\right)_{SF_6} \left(\%SF_6\right)^{0.18}. \tag{7}$$

4. **RESULTS AND DISCUSSION**

The experimental values of corona onset voltages (V_0) shown in Fig. 1 and Fig. 2, increase linearly with pressure and then tend towards saturation. The latter may be attributed to the change of the surface of the tip electrodes. 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 [13].

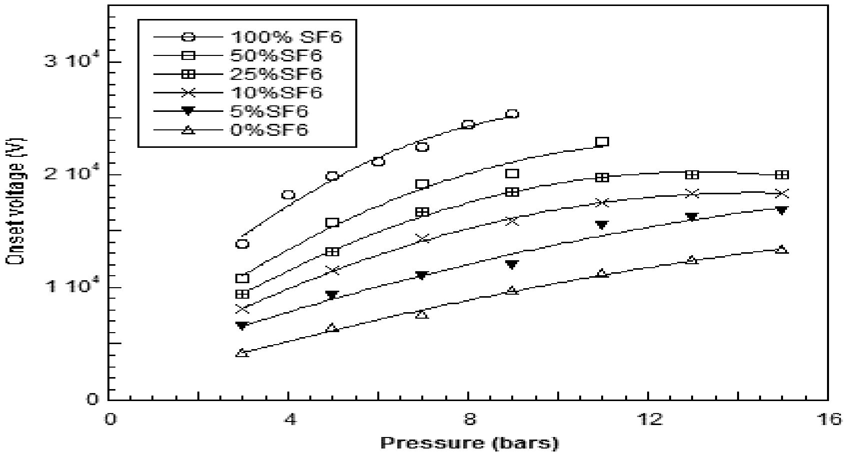

Fig. 1 – Measured onset voltages as a function of the gas pressure for different amounts of SF_6 for positive polarity.

The positive onset voltages are relatively higher compared with those measured in negative polarity [14]. 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 in the critical volume [15].

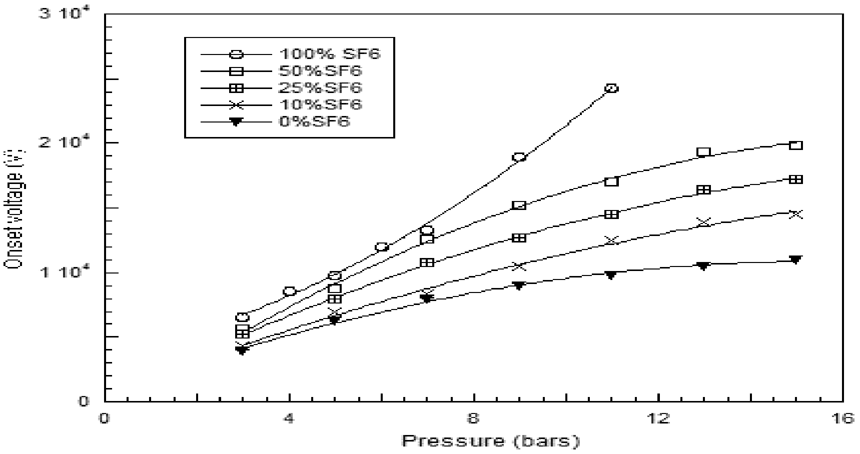

Fig. 2 – Measured onset voltages as a function of the gas pressure for different amounts of SF_6 for negative polarity.

Using eq. (6), the values of $(E/P)_{\lim}$ for mixtures calculated by Malik and Qureshi [11] and those obtained by Kline *et al.* [12] are recorded in Table 1.

Table 1

The values of $(E/P)_{lim}$ for SF_6-N_2 gas mixtures

SF_6 ratio	$(E/P)_{lim}$ in $kV.cm^{-1}.bar^{-1}$ (Malik and Qureshi [11])	$(E/P)_{lim}$ in $kV.cm^{-1}.bar^{-1}$ (Kline's formula[12])
100%	87.75	89
50%	74.2	78.6
25%	63.2	69.3
15%	56.6	63.2
10%	52.1	58.8
5%	43.9	51.9

The constant *C* is also determined by calculations using equation (4). In the Table 2, are presented the values of *C* found by Malik and Qureshi and our values calculated with $(E/P)_{lim}$ given by Kline's formula.

Table 2

Determination of the constant C

SF_6 ratio	*C* (Malik, Qureshi [11])	*C* (Kline [12])
100%	1.33	1.32
50%	1.64	1.61
25%	1.96	2
15%	2.29	2.3
10%	2.56	2.6
5%	3.1	3.2

It is shown in Table 2, that our values are very close to those of Malik and Qureshi, and that *C* is not very sensitive to the way $(E/P)_{lim}$ is calculated. We are now able to calculate V_0 for mixtures in our experimental conditions. Corona onset voltages calculated using Malik and Quershi's and Kline's models are compared with the measured values deduced from the current-voltage characteristics as a function of gas pressure for different amounts of SF_6 in the SF_6-N_2 gas mixture (Figs. 3–7). For a mixture of 5 % SF_6-95 % N_2 (Fig. 3) the onset voltage increases linearly with pressure up to 9 bar, then shows deviations from the theoretical behavior and tends towards saturation. Such behavior is often attributed to surface effects, which are more sensitive at high pressure [2, 16]. There is a small discrepancy between the empirical models, but both overestimate V_0. In Fig. 4, for a mixture of 10 % SF_6-90 % N_2 the empirical calculation does somehow coincide with the experimental results up to 10 bar. Beyond this limit the experimental values deviate and tend towards saturation.

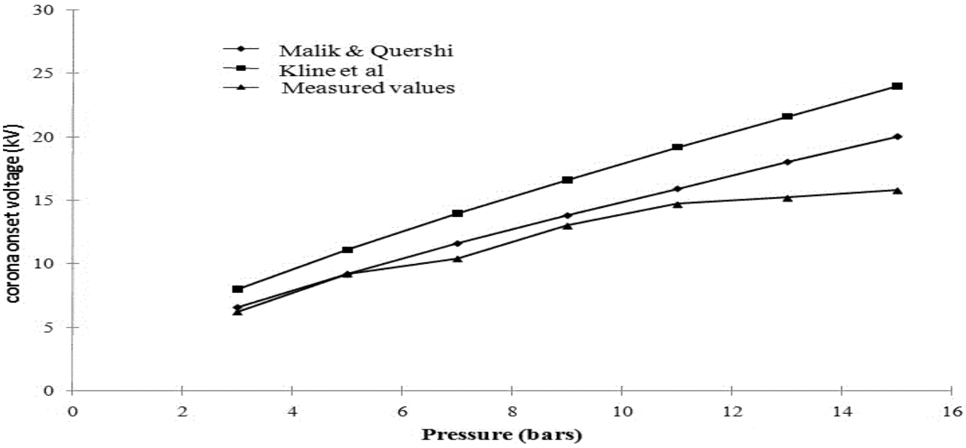

Fig. 3 – Corona onset voltages calculated using empirical models compared with the measured values as a function of gas pressure with 5% SF_6 in the SF_6-N_2 gas mixture.

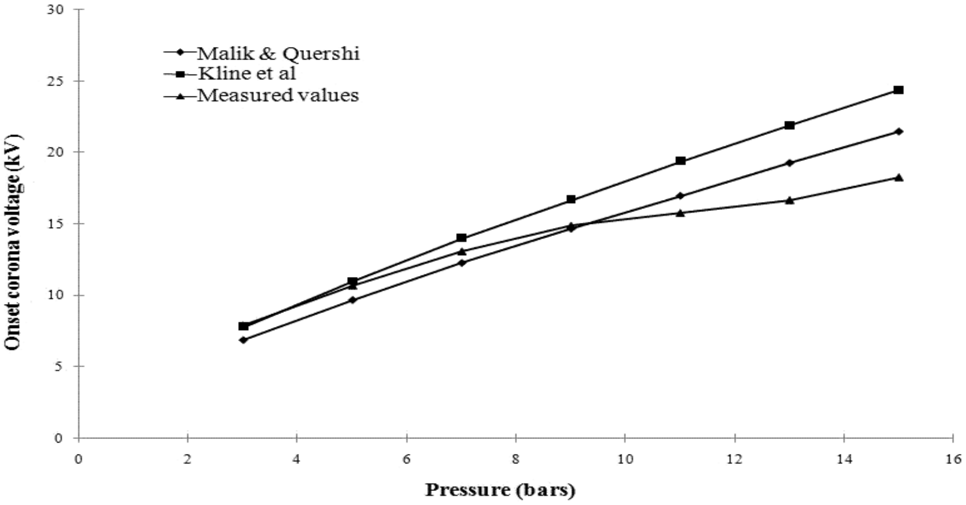

Fig. 4 – Corona onset voltages calculated using Malik and Quershi’s model and Kline’s model compared with the measured values as a function of gas pressure with 10 % SF_6.

For 25 % SF_6-75 % N_2 the calculated values are underestimated up to 10 bars and the gap between the models is reduced.

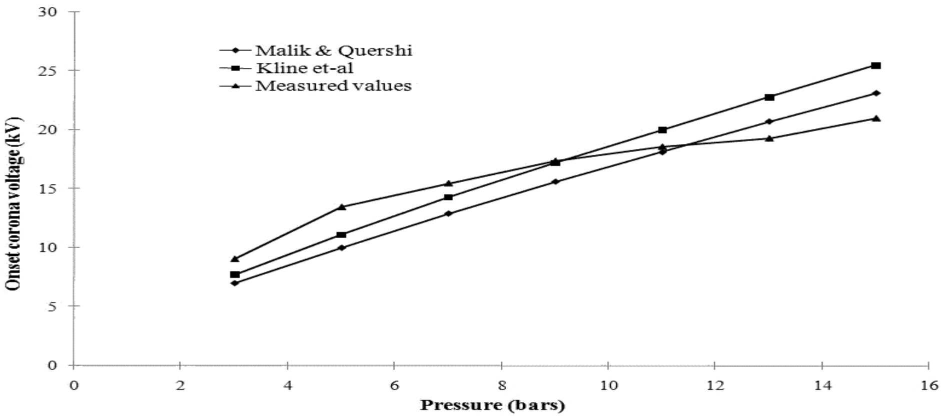

Fig. 5 – Corona onset voltages calculated using Malik and Quershi’s model and Kline’s model compared with the measured values as a function of gas pressure with 25 % SF_6.

In higher percentage of SF_6 in the gas mixture beyond 50 % the experimental results are higher than those calculated using empirical models. The difference between the two models is becoming smaller.

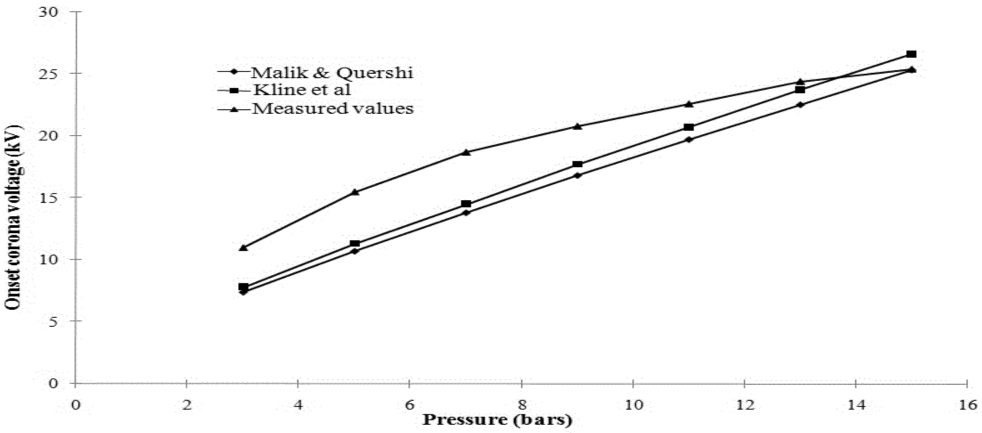

Fig.6 – Corona onset voltages calculated using Malik and Quershi’s model and Kline’s model compared with the measured values as a function of gas pressure with 50% SF_6.

The discrepancy between the empirical models decreases with the increase of the percentage of SF_6 in the gas mixture. With a 10 % of SF_6 in SF_6-N_2 gas mixture, there is somehow an agreement between the experimental and the calculated values. Obviously, in the application of the mentioned empirical formulae to the experimental data, they all met with some difficulties. Based on the experimental data extracted from the current-voltage characteristics and the knowledge of corona discharge, a new general formula is therefore, necessary to predict with accuracy the onset voltages for SF_6-N_2 gas mixtures.

5. **CONCLUSION**

The corona onset voltages measured increase linearly with pressure and then tend to saturate. The saturation may be attributed to the change of the surface of the tip electrode. Globally, when comparing the experimental results with the calculated values we can notice that the models overestimate V_0 for low SF_6 ratio ($\leq$ 5 % SF_6) and underestimate it for high pressures ($\geq$ 50 % SF_6).

Received on October 16, 2014

REFERENCES

1. L. Niemeyer, F. Y. Chu, *SF_6 and the atmosphere,* IEEE Transactions on Electrical Insulation, **27**, pp. 184–187, 1992.
2. L. G. Christophorou, R .J. Van Brunt, *SF_6/N_2 Mixtures: Basic and HV Insulation Properties*, IEEE Transactions on Dielectrics and Electrical Insulation, **2**, *5*, 1995.
3. F. Y. Chu, *SF_6 Decomposition In Gas-Insulated Equipment,* IEEE Transactions on Electrical Insulation, **EI-21**, *5*, 1986.
4. N. H. Malik, A. H. Qureshi, *A Review of Electrical Breakdown in Mixtures of Sulphur-Hexafluoride and other Gases*, IEEE Transactions on Electrical Insulation, **EI-14**, *1*, pp. 1–13, 1979.
5. E. Kuffel, A.Yializis, *Impulse Breakdown of Positive and Negative Rod-Plane Gaps in SF_6-N_2 Mixtures*, IEEE Transactions on Power Apparatus and Systems, **PAS-97**, *6*, pp. 2359–2366, 1978.
6. A. Lemzadmi, A. Gueroui, F. Beloucif, and A. Boudefel, *Characteristics of Corona Discharge in SF_6-N_2 Gas Mixture* , IEEE Proceedings of the World Congress on Engineering, WCE 2014, London, U.K., July 2–4, 2014.
7. Bob L. Henson, *A space- charge region model for microscopic steady coronas from points,* J. Appl. Phys., **52**, *2*, pp. 709–715, 1981.
8. Xiangbo Meng, Hui Zhang, Jingxu Zhu, *A general empirical formula of current-voltage characteristics for point-to-plane geometry corona discharges*, J. Phys. D: Appl. Phys., **41**, *6*, p. 065209, 2008.
9. T. Nitta, T. Y. Shibuya, *Electrical Breakdown of Long Gaps in Sulphur-Hexafluoride* , IEEE Transactions on Power Apparatus and Systems, **PAS-90**, *3*, pp. 1065–1071, 1971.
10. V. S. Kulkarni, A. S. Nema, *Calculation of Breakdown Voltages of Gaseous Insulation with Special Reference to Electronegative and their Mixtures*, 4th Int. Symp. on High Voltage Engineering, Athens, Greece, 5–9 September 1983.
11. N. H. Malik, A. H. Qureshi, *Calculation of Discharge Inception Voltages in SF_6/N_2 Mixtures,* IEEE Trans. on EI, **EI-14**, *2*, pp. 70–76, 1979.
12. G. Kline, *et al*, *Dielectric Properties for SF_6 and SF_6 mixtures predicted from basic data,* J. Appl. Phys., **50**, *11*, pp. 6789–6796, 1979.

13. V. K. Makdawala, D. R. James, L. G. Christophorou, *Effect of ionisation processes on the corona stabilisation breakdown in* SF_6 *and* SF_6*-mixtures*, 4th Int. Symp. On High Voltage Engineering, Athens, Greece, 5–9 September 1983.
14. Tomoyuki Hirata, Hideki Ueno, Hiroshi Nakayama, *Characteristics of* N_2/SF_6 *Mixture Gas in Creeping Discharge Developing in Narrow Gap with Backside Electrode*, Electrical Engineering in Japan, **158**, *2*, pp. 31–38, 2007.
15. F. A. M. Riszk, M. B. Eteiba, *Impulse breakdown voltage-time curves of* SF_6 *and* SF_6*-*N_2 *in coaxial cylinder gaps*, IEEE, Transactions on Power Apparatus and Systems, **PAS-101**, *12*, pp. 4460–4471, 1982.
16. Y. Qiu, I. D. Chalmers, *Effect of electrode surface roughness on breakdown in* SF_6*-*N_2 *and* SF_6*-*CO_2 *gas mixtures*, J. Phys. D: Appl. Phys., **26**, *11*, pp. 1928–1932, 1993.