Analytic Model of the Breakdown of Argon at Low Pressure in Combined Electric Fields

Iliycho Petkov Iliev, and Snezhana Georgieva Gocheva-Ilieva

***Abstract*—**In this study the breakdown curve of argon at low pressure in radio-frequency discharge within combined electric fields is considered. Based on experiment data, a new modified criterion has been proposed for the modeling of a breakdown curve. It has been found that there is very good correspondence with experiment results. A comparison has been carried out against the existing analytic criteria. This indicated that the suggested criterion describes experiment results more accurately.

***Keywords*—**Argon discharge, breakdown curve, modified criterion, radio-frequency discharge.

I. Introduction

THE radio-frequency (RF) capacitive discharge at low pressure is used in a wide range of plasma processes applied in technologies, engineering and scientific research. It is utilized in the manufacture of semiconductor products (for the cleaning of semiconductor pads), making of thin layers, and performing chemical analyses of materials. Interest in the high-frequency discharge is also motivated by the possibility of obtaining new data on the interactions of electrons with atoms and ions. This type of discharge is also used to pump gas lasers and metal vapor lasers [1].

The application of this type of discharge relies on knowledge about the instability and breakdown conditions which may cause the gas discharge device to deviate from the preset operation mode. For this reason, experiment measurements and mathematical simulations of breakdown curves in direct current (DC) discharge, RF discharge, and combined electric and magnetic fields discharge are of particular interest.

Argon is widely used in plasma technology and is also an important gas in scientific studies. It is considered that there has been no satisfactory fitting of measured and predicted breakdown voltages for argon [2, 3]. Two basic approaches are used to obtain such fitting. The first involves examining collision processes in the plasma in order to determine the distribution function according to particle energy or to construct appropriate analytical models using molecular constants. The second approach is based on experiment data which are utilized to construct computer models and run simulations using probability methods, for instance such as the particle-in-cell/Monte Carlo collision (PIC/MCC) type methods (see [2, 3, 4] and the publications cited therein).

It has been found that the application of weak DC voltage to a high-frequency discharge causes a notable increase of breakdown voltage in a high-frequency discharge on the right side of the breakdown curve [5]. The additional direct voltage increases electron losses due to drift from electrodes. This leads to an increase in discharge pressure and voltage. The minimum of the breakdown curve shifts towards higher voltages and pressures.

The aim of this study is to use the available experiment data to obtain a new analytic criterion, describing the breakdown curve of argon at low pressure in combined electric fields by defining the breakdown voltage U_{rf} as a function of the parameter *pd*, where *p* is gas pressure and *d* is the distance between electrodes in the gas discharge chamber. The derived criterion gives an improved modification of the known criterion from [4] and develops the criterion obtained for argon in RF fields as given in [6].

II. Problem Set

For a high-frequency discharge, where the breakdown is dominated by the ionization of molecules by electrons and the diffusion of electrons to the discharge chamber walls, the breakdown criterion assumes the following form:

$$\frac{\upsilon_i}{D_e} = \frac{1}{\Lambda^2} \tag{1}$$

where υ_i is the frequency at which molecules are ionized by electrons, D_e is the electron diffusion coefficient, Λ is the diffusion length, dependent on the geometry of the gas discharge chamber [3, 4]. When deriving criterion (1), it is assumed that the diffusion coefficient of electrons is an isotropic function, i.e. it is not dependent on the direction of electron movement.

In a weak DC electric field, criterion (1) takes the following form [4]:

$$\frac{\upsilon_i}{D_e} = \frac{1}{\Lambda^2} + \left(\frac{E_{dc}}{2D_e / \mu_e}\right)^2 \tag{2}$$

Where, μ_e is the coefficient of electron mobility, E_{dc} is the intensity of the DC field. In this case, criterion (2) may be

Iliycho Petkov Iliev is with the Technical University of Sofia, Branch Plovdiv, 25 Tzanko Djusstabanov Street, 4000 Plovdiv, Bulgaria (e-mail: iliev55@abv.bg).

Snezhana Georgieva Gocheva-Ilieva is with the Plovdiv University "Paisii Hilendarski", 24 Tzar Assen Street, 4000 Plovdiv, Bulgaria (corresponding author's phone: 00359265842; e-mail: snow@uni-plovdiv.bg).

presented in the form [4]

$$\left(A_1 pd - \frac{A_1 \lambda U_{rf}}{\sqrt{2} B_0 C_2 d}\right) \exp\left(-\frac{B_0 pd}{\sqrt{2} U_{rf}}\right) = \left\{1 + \left[\frac{U_{dc}}{U_{rf}}\left(A_1 pd - \frac{A_1 \lambda U_{rf}}{\sqrt{2} B_0 C_2 d}\right)\left(\frac{c_i \rho}{2\sigma}\right)^{1/2}\right]^2\right\}^{1/2} \quad (3)$$

Where, $A_1, B_0, C_2, c_i, \lambda, \sigma, \rho$ are molecular constants and U_{dc}, U_{rf} are respectively the DC and RF discharge voltages.

Up to now, when considering this problem, it has not been taken into account that RF forms its own DC field. Its value can be estimated by the empirical dependency [1]:

$$U_{dc} = U_{rf} / \pi \quad (4)$$

Therefore, in order to use criterion (2), it is not necessary to apply an external electric field.

Subsequently, using known dependencies $\upsilon_i \approx \alpha v_d \approx \alpha \mu_e E$, where α is the coefficient of gas volume ionization and v_d is the drift speed of electrons, criterion (2) may be represented in the form

$$\frac{\alpha E}{D_e / \mu_e} = \frac{1}{\Lambda_e^2} + \left(\frac{E_{dc}}{2D_e / \mu_e}\right)^2 \quad (5)$$

Usually the volume ionization coefficient α is approximated in the form $\frac{\alpha}{p} = A \exp\left(-\frac{B}{E/p}\right)$, where *A*, *B* are constants. Based on experiment data, the D_e / μ_e ratio can be approximated by

$$\frac{D_e}{\mu_e} = M + N \frac{E}{p}$$

using suitably defined constants *M*, *N*. The diffusion length Λ for flat configurations is given by the expression $\frac{1}{\Lambda^2} = \left(\frac{\pi}{d}\right)^2$.

In this manner, criterion (2) may be written as

$$\frac{U_{rf}\, pdA \exp\left(-\frac{Bpd}{U_{rf}}\right)}{M + N \frac{U_{rf}}{pd}} - \frac{U_{rf}^2}{\left[2\pi\left(M + N \frac{U_{rf}}{pd}\right)\right]^2} - \pi^2 = 0 \quad (6)$$

Criterion (6) is used in [6] to estimate the breakdown curve in argon discharges. This yielded very good correspondence with known experiment results.

III. Model Construction

In the presence of an external electric field, criterion (2) needs to be modified. The quantity E_{dc} has to be replaced by $E_{dc,\Sigma}$, which results from the interaction of the two fields - internal ($E_{dc,in}$) and external ($E_{dc,ex}$), respectively. More specifically, it is true that:

$$E_{dc,\Sigma}^2 = E_{dc,in}^2 + E_{dc,ex}^2 + 2E_{dc,in}E_{dc,ex}\cos\beta \quad (7)$$

Where, β is the angle of interaction between the two fields. As a result, criterion (6) assumes the following form

$$\frac{U_{rf}\, pdA \exp\left(-\frac{Bpd}{U_{rf}}\right)}{M + N \frac{U_{rf}}{pd}} - \frac{U_{rf}^2 + \pi^2 U_{dc}^2 + 2\pi U_{rf} U_{dc} \cos\beta}{\left[2\pi\left(M + N \frac{U_{rf}}{pd}\right)\right]^2} - \pi^2 = 0 \quad (8)$$

Here $U_{dc,in} \approx E_{dc,in} d$ and $U_{dc,ex} \approx E_{dc,ex} d$ are the values of the applied internal (intrinsic) and external voltage, respectively.

We will consider two boundary cases:

- $\beta = 180^0$. In this case, the two fields have opposite directions. The resulting field is the smallest: $E_{dc,\Sigma} = E_{dc,in} - E_{dc,ex}$. Criterion (8) takes the form:

$$\frac{U_{rf}\, pdA \exp\left(-\frac{Bpd}{U_{rf}}\right)}{M + N \frac{U_{rf}}{pd}} - \left[\frac{U_{rf} - \pi U_{dc}}{2\pi\left(M + N \frac{U_{rf}}{pd}\right)}\right]^2 - \pi^2 = 0 \quad (9)$$

- $\beta = 0^0$. The two fields have the same direction and the resulting field takes its maximum value: $E_{dc,\Sigma} = E_{dc,in} + E_{dc,ex}$. In this case, criterion (8) has the following form:

$$\frac{U_{rf}\, pdA \exp\left(-\frac{Bpd}{U_{rf}}\right)}{M + N \frac{U_{rf}}{pd}} - \left[\frac{U_{rf} + \pi U_{dc}}{2\pi\left(M + N \frac{U_{rf}}{pd}\right)}\right]^2 - \pi^2 = 0 \quad (10)$$

For argon, the values of approximation constants are given in Table 1. The values of *A* and *B* are obtained for experiment data given in [7], while the values of *M* and *N* are obtained from experiment data in [8].

TABLE I
Constants Used in the Model Criteria

Constant	Value
A	5.91189
B	108.76559
M	1.052994
N	0.04039617

IV. Discussion with Conclusion

The obtained results from the derived analytical criteria are

http://dx.doi.org/10.15242/IIE.E0514066

graphically represented in Fig. 1 and Fig. 2 and are compared with other criteria, existing in literature, as well with experimental data.

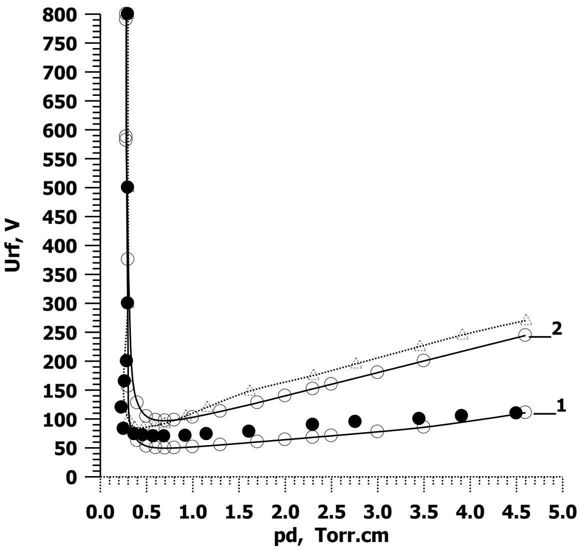

Fig. 1 Theoretical and experimental breakdown voltage curves for applied external voltage $U_{dc} = 25V$ in argon discharge at low pressure: ○-1 - as per criterion (9), ○-2 - as per criterion (10), • - experiment data [4] , Δ - as per criterion (3) from [4].

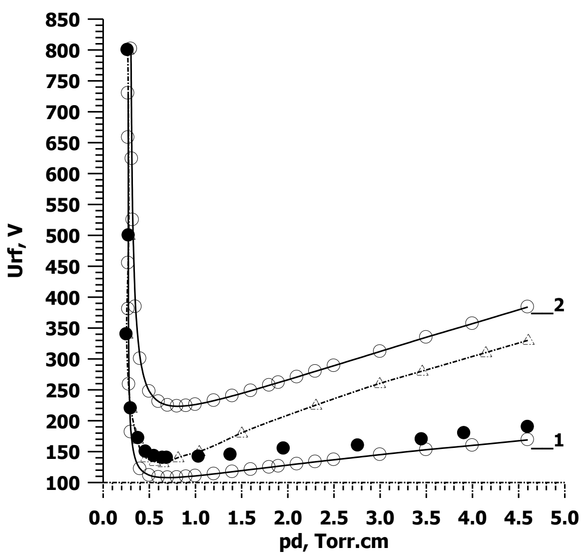

Fig. 2 Theoretical and experiment breakdown voltage curves for applied external voltage $U_{dc} = 100V$ in argon discharge at low pressure: ○-1 - as per criterion (9), ○-2 - as per criterion (10), • - experiment data [4] , Δ - as per criterion (3) from [4].

Fig. 1 and Fig. 2 show that criterion (9) provides very good correspondence with experiment data. This criterion gives much more accurate predictions of the breakdown voltage in the right section of the experiment breakdown curve as compared to (3) which is derived in [4].

In conclusion, a simple analytical criterion for building the breakdown curve of an argon RF discharge in combined electric fields is obtained. This yielded very good correspondence with known experiment results. Criterion (9) provides better correspondence with experiment data when compared to (10). This leads us to believe that with the existing experiment setup in [4] the two fields have opposite directions.

V. Acknowledgments

This work was supported by the NPD of Plovdiv University Paisii Hilendarski, Bulgaria, grant NI13 FMI-002.

References

[1] Yu. P. Raizer, M. N. Shneider, and N. A. Yatsenko, *Radio-Frequency Capacitive Discharges*. New York: CRC Press, 1995.

[2] M. Radmilović-Radjenović and J. K. Lee, "Modeling of breakdown behavior in radio-frequency argon discharges with improved secondary emission model," *Phys. Plasmas*, vol. 12, pp. 063501-1 - 063501-8, 2005.

[3] M. Radmilović –Radjenović and B. Radjenović, "Modeling of a low-pressure argon breakdown in combined fields," *Plasma Sources Sci. Techn.*, vol. 15, pp. 1-7, 2006. http://dx.doi.org/10.1088/0963-0252/15/1/001

[4] M. Radmilović -Radjenović, J. K. Lee, and Z. Lj. Petrović, "Low-pressure argon breakdown in combined dc and rf fields," in *Proc. XXVIIth ICPIG*, Eindhoven, the Netherlands, 18—22 July, 2005, Topic number 17.

[5] V. A. Lisovskiy and V. D. Yegorenkov, "Low-pressure gas breakdown in combined fields," *J. Phys. D.: Appl. Phys.*, vol. 27, pp. 2340-2348, 1994. http://dx.doi.org/10.1088/0022-3727/27/11/014

[6] I. P. Iliev, S. G. Gocheva-Ilieva, and N. V. Sabotinov, "Modelling of radio-frequency breakdown in argon," *Optoelectron. Adv. Mat*., vol. 11(10), pp. 1392-1395, 2009.

[7] *Handbook of Physical Quantities*, Moscow: Energotomizdat, 1991.

[8] V. A. Lisovskii, "Determination of electron transport coefficients in argon from ignition curves of rf and combined low-pressure discharges," *Tech. Phys. Lett.*, vol. 24(4), pp. 308-310, 1998. http://dx.doi.org/10.1134/1.1262093