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# Study of the Weak to Heavy-Current Transition in High-Frequency Discharge in Nitrogen

**Iliycho Iliev and Snezhana Gocheva-Ilieva**

**Abstract:** Variety of electron, ion and plasma technologies as well as gas discharge devices operate in fixed form of the discharge. The transition from weak to heavy-current in radio-frequency low-current discharge leads to instabilities in physical processes and it is very critical for the normal functionality of the technology or device. In this paper by means of Townsend criterion the influence of the incoming electric power and voltage on this transition in a cross-section of the discharge is numerically simulated. The calculations show a possible change of applied designed power up to 32% without weak to heavy-current transition. It is also obtained that the rise in 40% of the pressure can change the critical breakdown power only up to 12%. These results are in agreement with the simple analytical one-dimensional models and experimental data.

**Keywords:** Nitrogen discharge, radio-frequency, breakdown, instability.

## 1 Introduction

During the usage of various high-voltage devices (transformators, high-power cables, commutators), as well as during the evaluation of the outside conditions (temperature, moisture, pressure, dust loading, voltage peak) sparks, arcs and plasma columns, have appeared, which cause the deterioration of the device. A number of electron, ion and plasma technologies and gas-discharge devices work at a strict form of the gas discharge. Any transition into another form of the discharge may cause a violation of its normal technological conditions and can finish by making the technology or device unusable. It is necessary that the gas discharge devices can operate in the given form of a gas discharge without entering another state.

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I. Iliev is with Technical University of Sofia - brunch Plovdiv, Tzanko Dusstabanov 25, 4000 Plovdiv, Bulgaria (e-mail: iliev55@abv.bg). S. Gocheva-Ilieva is with University of Plovdiv, Tzar Assen 24, 4000 Plovdiv, Bulgaria (e-mail: snow@pu.acad.bg).

Because of this the theoretical and experimental evaluation of the resistance of the gas discharge devices is an actual task. This problem involves the determination of admissible borders of variation of the outside parameters in which the form of the discharge does not change. Studying the physical processes for instability helps to develop new engineering methods in order to improve the operational stability of the gas discharge devices.

One of the forms of the gas discharge is the high-frequency capacitive discharge (f=13.56 MHz). It is applied in a number of gas discharge devices (gas lasers and metal vapor lasers), in plasma technologies for production of thin layers, for exploring the chemical components of the materials. This type of discharge has a number of advantages compared to the other discharges: high volume power density (up to 400 mA/cm$^2$), high current density (up to 30 W/cm$^3$), stability of the discharge, simple and reliable constructions of the devices.

The high-frequency capacitive discharge exists in two forms: weak-current discharge ($\alpha$ discharge) and heavy-current form ($\gamma$ discharge). The weak-current form is described by a small volume density (5-30 W/cm$^3$) and weak-current density (1-10 mA/cm$^2$). It is characterized by the effect of a constant current density. The thickness of the charged particles layer in the electrode region (electrode layer) is in order of 0.3 cm. The conduction current is dominant. It can be also mentioned that the relative part of the positive ions is very small and is about $10^{-3}$ from the total current. The $\alpha$ discharge is used as a working environment for gas lasers and metal vapor lasers, as well as for production of thin layers. The weak-current form has a number of advantages: it works at lower currents on the electrodes, the gas discharge is easily controlled (electron density, electrical power), it gives minimal losses of electrical power in the electrode layers.

The heavy-current form is characterized by a bigger current density (0.12 A/cm$^2$) and a bigger power density (400 W/cm$^3$). In these conditions the law of the current's permanent density is not valid. The thickness of the charged particles layer in the electrode region is smaller (0.05 cm). The ion current is significantly greater and comes up to 20-25% from the total current.

By increasing the electric power, a transformation of the $\alpha$ discharge occurs. The current rapidly increases and the discharge is tightened in a fine plasma column. A fast increase of the conduction and displacement currents is observed. The local temperature around the electrodes increases. This leads to additive contraction of the discharge and an amplification of the thermo-ionization processes. In the molecular gases (also in nitrogen) a bigger part of the electron energy initially is used for stimulation of the fluctuating levels of the molecules. After that, due to the fluctuating relaxation this electron energy transforms into a thermal form (i.e. the increase of the thermal velocity of the molecules is gained).

For the nitrogen the time of the fluctuating relaxation is relatively long (0.12

s) and the time for the diffusion is of order of $10^{-2} - 10^{-3}$ s. This means that in a particular case, depending on the geometric design, a part of the energy can give up the discharge volume's bounds, and this can influence on the stability of the nitrogen discharge. However, the experiments in conditions similar to the observed ones show that the fluctuating relaxation succeeds in completing itself and only neglected part of the energy can leave outside of the discharge [1].

The processes of the secondary electron emission from the electrodes ($\gamma$ processes) are strengthened. A heavy-current form ($\gamma$ discharge) occurs [1]. For this reason the condition for the transition between the $\alpha$ and $\gamma$ regimes of the discharge is a subject of experimental and theoretical studies (see [1] and the there quoted literature). The examined there theoretical studies are one-dimensional, which considerably simplifies the given task and does not all a full understanding of the processes, connected with the instability of the discharge.

Here we set the task to investigate the condition for the transition between $\alpha$ and $\gamma$ regimes as a function of the incoming electric power. This problem occurs mostly during the usage of gas discharge devices. An accidental occurrence of a peak current usually causes ion instability, which may causes the gas discharge device deterioration. Other important applied characteristic is an approximate determination of the borders of stability in an accidental rise of the electric power.

## 2 Subject of Study

Without loss of community, we observe a real gas discharge device, working in the conditions of a high-frequency capacitive discharge [1]. Its main geometrical design is shown on Fig. 1. The device consists of two tubes: an outer, made of quartz, and an inner, made of $Al_2O_3$. The pressure of the inert gas nitrogen is $p = 5$ Torr, the powering frequency is $f = 13.56$ MHz.

The main task of the presented model is to optimize the described system. The reaction of the system is evaluated by changing the initial parameters (geometric sizes, type and pressure of the inert gas, electric power). The goal is to estimate the relative impact of each parameter on the general behavior of the system. In this way it is possible to determine the most probable parameters for the optimal work of the device. This gives opportunities for engineer's effort automation, in order to raise the efficiency of the scientific research by winning time and reducing costs.

The transition between weak and heavy current regimes is investigated by means of the Townsend's criterion [2]:

$$\int_l \alpha \, dl = \ln(1 + \frac{1}{\gamma}) \qquad (1)$$

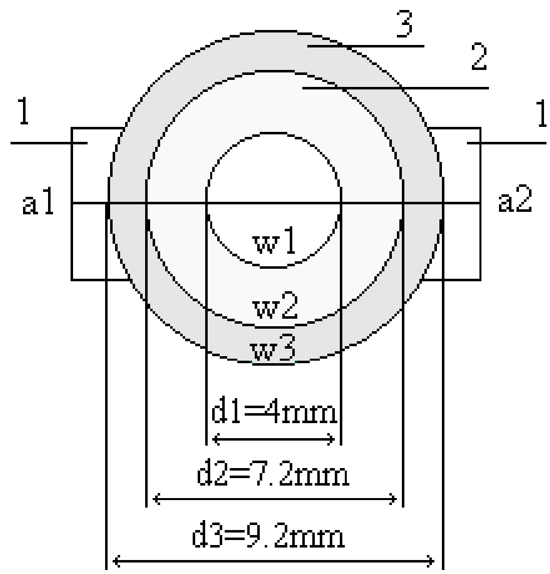


Fig. 1. Geometrical design of the cross-section of a discharge device: 1-external electrodes; 2-$Al_2O_3$ tube; 3-quartzous tube.

where $\alpha$ is the volume ionization coefficient, $\gamma$ is the secondary emission coefficient, $l$ is the line of the maximum electron amplification.

In order to apply the criteria (1) the values of the electric field intensity in the cross section of the gas discharge are needed. Their determination was thoroughly described in [3, 4], this is why we will not pay special attention to it here. We will briefly describe the method for solving the problem and we will use part of the results (see Fig. 2 and Fig. 3). The proposed here model for calculating the electric field is of a hybrid-theoretically-experimental type. It is based on the fluid model while there is a vast usage of experimental data: drift velocity, diffusion coefficients, volume ionization, heat conductivity, distribution of the charged particles in the cross-section of the discharge. This approach differs from the existing theoretical models (see for instance [1] and the quoted there literature).

The intensity $E$ of the electric field is defined by the formula

$$E(x,y) = -\text{grad}\, U(x,y). \tag{2}$$

Here the distribution of the scalar potential $U(x,y)$ in the cross section of the gas discharge is carried out by solving the two-dimensional Poisson quasistanionary equation

$$\frac{\partial^2 U(x,y)}{\partial x^2} + \frac{\partial^2 U(x,y)}{\partial y^2} = -\frac{e}{\varepsilon_0}[n_i(x,y) - n_e(x,y)], \tag{3}$$

where $e$ is the electron charge; $\varepsilon_0$ is the dielectric constant; $n_i(x,y)$ and $n_e(x,y)$ are the concentrations of ions and electrons, respectively.

The solution was found under the next mixed boundary conditions:

- along the outer metal body casing:

$$U_\Gamma = 0, \tag{4}$$

- along the two outer electrodes respectively:

$$U_L = 0, \tag{5}$$

$$U_R = 0, \tag{6}$$

- at the border between the walls of the two tubes:

$$\varepsilon_i E_{in} = \varepsilon_j E_{jn}. \tag{7}$$

Boundary condition (4) presents the fact, that the gas discharge device in terms of electrical safety is placed in a metal body casing, which is grounded and has a constant potential of zero. Boundary conditions (5)-(6) show, that the left electrode is grounded, while the right is the rf-powered electrode. Condition (7) reflects the criteria for the field intensity at the borders of two dielectrics. Here $E_{in}$ and $E_{jn}$ denote the normal components of the electric field, and $\varepsilon_i$ and $\varepsilon_j$ denote the dielectric permittivities of the materials of the walls.

Some numerical results for the potential and the intensity are represented in the next Fig. 2 and 3 [3] .

Fig. 2 shows the distribution of the scalar potential in the cross section of the gas discharge at mean volume power $q_v = 4.5\text{W/cm}^3$ and mean density $j = 5.8\text{mA/cm}^2$. Fig. 3 shows the distribution of the intensity of the electric field between the two electrodes along the line $a1 - a2$ (see Fig. 1).

We did not dispose of enough reliable literary data for the values of the electric field intensity concerning our described configurations. It is known that the classical methods using sondes are impracticable because of the disturbances in the measuring appliances, caused by the high frequency of the incoming power. Alternatively, indirect methods can be used to explore the parameters of the gas discharge: optical methods (photography), laser spectroscopy or laser-induced fluorescence (LIF) method and laser optogalvanic (LOG) method. These methods in principle don't allow sufficient accuracy to determine the values of the electric field.

The obtained results for the electric field intensity have a good quantity coincidence with respect to the results from simple one-dimensional models and experimental results for discharges, operating at similar conditions, given in [1], [5], and [6].

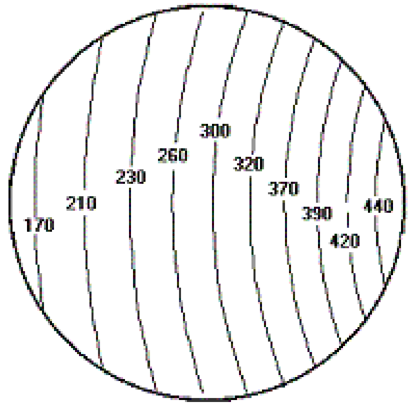


Fig. 2. Distribution of the potential in $V$ at mean volume power $q_v = 4.5$W/cm$^3$ and mean density $j = 5.8$mA/cm$^2$.

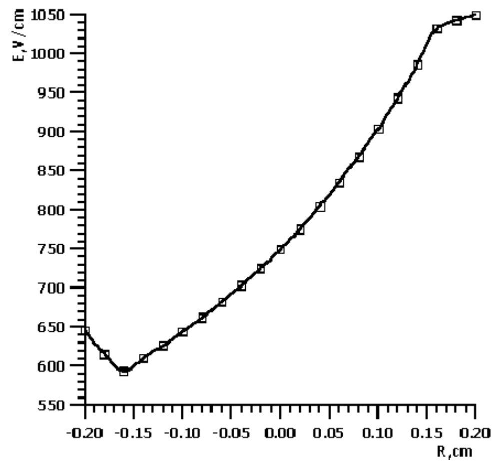


Fig. 3. Distribution of the electric field intensity at mean volume power $q_v = 4.5$ W/cm$^3$ and mean density $j = 5.8$mA/cm$^2$.

## 3 Numerical Discussion of the Transition between $\alpha$ and $\gamma$ Regimes in the Cross Section of the Device

We apply criteria (1) by setting the value of $\gamma = 0.01$, for the nitrogen at $E/p = 27 \div 200$V/(cm Torr) and $\alpha/p = 8.8exp(-275\,p/E)$ [7]. Numerical calculations show, that the line for the maximum electron amplification is the shortest distance between the electrodes along the central line $a1 - a2$ (Fig. 1, difference $dl$).

Given the initial value of the power ($q_v = 4.5W/cm^3$) the criteria (1) will not be valid, which shows, that the device works well at this power in the given $\alpha$ gas discharge form. During the following computer simulations we raise the mean power density while maintaining a regime of constant current density ($j = 5.8$mA/cm$^2$). For every intermediate power value the input condition (1) is verified. Fig. 4 shows the function $y = \int_l \alpha \ df(q_v)$. The equality (1) $y = \int_l \alpha \ dl = \ln(1+1/\gamma) = 4.615$ stays valid at relative increase in the volume power density $q_v/q_{v0} \approx 1.32$, as with the breakdown power $q_{vp} = 5.94$W/cm$^3$.

For a rf-nitrogen discharge, working in similar conditions ($p = 25$Torr) an experimental voltage breakdown at $U_{p1} = 270$V have been adduced in [1]. For the same discharge also in [1], by means of a one-dimensional analytical model the value of the voltage breakdown at $U_{p2} = 330$V have been established, giving an error of 22% with regard to the experimental one.

In our geometric configuration (see Fig. 1) and a nitrogen pressure $p = 5Torr$ for a breakdown power $q_{1p} = 5.94$W/cm$^3$ the breakdown voltage of $U_{p3} = 310$V was obtained, so the relative error is of 10%. This result is in a good accordance

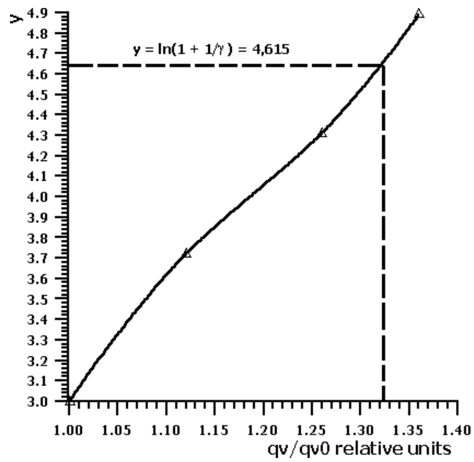


Fig. 4. Dependence of $y = \int_l \alpha\ dl$ as a function of the relative power increase.

to the upper ones from [1], as well to our previous results in [8]. This shows that our developed model is precise and effective to describe the mutual dependence of the processes in the gas discharge and can be used in reasonable bounds for its optimization.

## 4 Analysis of the Results

The suggested method allows preliminary determination of the approximate electric power that is critical for giving rise to ion instability and $\alpha$ to $\gamma$ transition. In our considerations an accidental rise in designed power over 32% is critical for the reliable work of the device. In the case where the device is needed to operate at higher power than projected, the suggested method can be applied in advance in order to test different engineering solutions. In example, an increase in the pressure of the inert gas always makes ion instability less likely to occur because of a decrease in the kinetic energy of the electrons in consequence of the elastic collisions with the molecules of the inert gas.

The possibility of a relative increase in breakdown power at relative rise in nitrogen pressure (under initial conditions $p_0 = 5$Torr, $q_{vp0} = 5.94$W/cm$^3$) is shown in Fig. 5. An increase in pressure by 40% causes a rise in critical breakdown power by only 12%. The larger pressure can change the temperature profile of the discharge, energetical and gas-kinetical characteristics of the plasma and alter the technological characteristics of the device, rendering it useless, in spite of it operating in $\alpha$ discharge conditions. It is for this reason, that the suggested method has limited capabilities.

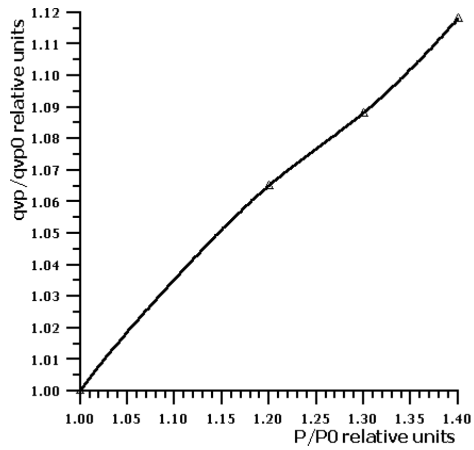


Fig. 5. Variation of the relative breakdown power as a function of the relative rise of the nitrogen pressure.

## 5 Conclusion

The suggested two-dimensional model, based on the beforehand calculation of the potential and intensity of the electrical field, allows the most probable boundary of stability work of the gas-discharge device to be defined. The calculations have shown that the effective operation of the device at an alteration in power supply within 32% is possible. The suggested method provides greater possibilities than the demonstrated ones. It has some universality and can easily be modified. With certain finishing touches it is possible that it not only measures the influence on the gas pressure, but also on the change in geometrical design, the presence of different add-ons to the main gas, and extra constructive elements on ionization stability of the device.

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