Applying the Different Statistical Tests in Analysis of Electrical Breakdown Mechanisms in Nitrogen Filled Gas Diode

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Abstract This paper presents the results of our investigations of breakdown mechanisms, as well as a description of their influence on the distributions of time delay distributions, for a gas tube filled with nitrogen at 4 mbar. The values of the time delay are measured for different voltages, and the values of the relaxation times and their distributions and probability plots are analyzed. The obtained density distributions have Gaussian distributions and exponential distributions for different values of relaxation times (Gaussian for small values and exponential for large values of relaxation time). It is shown that for middle values of relaxation time the delay distributions have a shape between Gaussian and exponential distributions, which is a result of the different influences of electrical breakdown.

Keywords: electrical breakdown, time delay density distributions, probability plots, nitrogen

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(Some figures may appear in colour only in the online journal)

1 Introduction

Investigations of gas discharges are significant for our understanding of the mechanisms used in many commercial gas discharge components. One of more significant problems in many commercial gas discharge components is time delay (delay response). The time delay \( t_D \) can be defined as the time interval between the applications of the sufficient voltage on electrodes and the electrical breakdown [1]. This time is a consequence of the time to reach the conditions necessary for electrical breakdown in gases.

Electrical breakdown is the transition from the insulator to the conducting state. The multiplication processes which lead to increasing the number of free electrons have a pronounced statistical nature, and consequently the electrical breakdown is a statistical behavior. The mechanisms of electrical breakdown in gases in experiments with small overvoltages and small pressures can be described with Townsend’s theory [2]. In these cases, the influence of the space charge to electrical breakdown can be neglected. According to the Townsend theory the theory breakdown criterion is:

\[
\gamma \left( e^{\alpha d} - 1 \right) = 1, \quad (1)
\]

where \( \alpha \) and \( \gamma \) represent coefficients of the primary ionization and effective secondary ionization (which includes all secondary processes), respectively. In contrast, for large values of pressure and overvoltages (when the effect of the space charge is very significant), the streamer model of the electrical breakdown in gases is used [2]. The transition regime between these two electrical breakdown mechanisms has previously been explained [3]. For nitrogen at 13.3 mbar pressure, the Townsend theory for electrical breakdown can be applied for overvoltages lower than 110% [4].

The electrical breakdown mechanism in gases can be treated like a sum of two apparent processes. The first process corresponds to the creation of an initial electron. The corresponding time for initial electron creation is determined with the physical processes (one or several), which leads to the creation of the initial electron. The appropriate time interval is called a statistical time delay \( t_S \), and it is described with the exponential distribution [1]. The second is the process in the gas which leads to the low impedance gas between the electrodes, i.e. leads to electrical breakdown. This process can be named the formative time delay \( t_F \). Commonly, the ionization of gas particles (atoms or molecules) until the breakdown is a consequence of many events, and accordingly has a high probability. Consequently, the corresponding formative time \( t_F \) can be described by a normal distribution [5,6]. Thus, the time delay \( t_D \) can be represented as a sum of \( t_S \) and \( t_F \) \((t_D = t_S + t_F)\) [1].

The distributions of total time delay have previously been investigated using different theoretical presumptions. For example, the convolution time delay model [5] is developed under presumption about the
independent statistical and formative time delay. In contrast, in Ref. [7] it is assumed that $t_S$ and $t_F$ are dependent values of $t_S$ and $t_F$ for small relaxation time $\tau$ (where the relaxation time $\tau$ is the time interval between the two successive measurements, without the voltages on the electrodes). Under this presumption, the authors describe the time delay distributions with Gaussian, Gauss-exponential and exponential log-normal shaped distributions. In addition, in many earlier papers the statistical nature of formative time delay was neglected [1] and it is treated only as a shifting parameter.

The time delay values and their distributions depend on many experimental parameters, overvoltages [8–10], relaxation times (i.e. time between two successive measurements without voltages on electrodes) [9,10], glowing time, current through diode, auxiliary glow current [10], gap between electrodes [8], and irradiation with UV and gamma radiations [11,12]. The time delay measurement method also imparts a lot of very important information about the working of many commercial gas discharge components, for example: starters [13,14] gas indicators [15], and gas arresters [16].

## 2 Experiment

The time delay values are measured with the “gasmem v1.0” system [17]. In this system the time delay is treated as the time interval between two different events in an electrical circuit, in which the gas diode is connected. The first of these events is the moment of application of the voltage $U_W$ on the gas diode, and the second event is the moment when the adequate current $I_G$ appears, which represents the 0.9$I_G$, when $I_G$ is the current in the gas tube. The measurement system is designed to control all of the significant experiment parameters, including the current through the gas $I_G$, glowing time $t_G$ and relaxation time $\tau$. In the course of the period $t_D$, the electrical current in the gas rises from zero to the current value $I_G$. In the course of the period $t_D$, the voltage $U_W$ is applied on the tube, and the current through the tube is $I_G$. No voltage is applied in the relaxation $\tau$ interval on the gas diode. The block scheme of the measurement system is given in Fig. 1.

The measurement system can be schematically represented as a three module system, which are the control module, analog switch module and voltmeter module. The first is the control module, and the main part of this module is a PIC18F4550 MCU. The internal timers in this module measure the time values. The control module is connected to a computer via a USB2.0 module. Their principal function is to control the analog switch module. The switch module turns the voltage on and off, and measures the time values. These two modules are electrically isolated with optocouplers. The third is a voltmeter module, which is based on a PIC16F887 MCU with an internal 10-bit analog-to-digital (A/D) converter. This module is created to measure the values of $I_G$ and to regulate the values $I_D$. The details of the measurement system are given in Ref. [17].

The maximal value of voltage rise time in the measurement system is 400 ns for $U_W$=900 V. The minimal time delay value is 800 ns, which is hardware limit of this measurement system. The relaxation time and glowing time values can be varied in intervals from 1 ms to $2^{12}$ ms ($\approx 50$ days).

The measurements are performed on a nitrogen filled gas diode, with a volume of 40 cm$^3$. The electrodes are made from iron. They have a spherical shape and are 8.5 mm in diameter. The distance between the electrodes is 3 mm. The gas tube was created on the basis of the X-ray tube standard. The gas tube is first vacuumed to $10^{-7}$ mbar and baked out at 350°C, and is finally filled with nitrogen. The tube was then filled with spectroscopy pure nitrogen at a pressure of 4 mbar. Before the measurement, the tube was conditioned with a current of 0.3 mA for 30 min. The existence of any systematic trend through measurement, i.e. randomness of measured values, is checked by Wilcoxon test [18,19]. This test shows any systematic trend not observed on confidence levels of 95% and 99%, i.e. the measured values are randomly distributed.

## 3 Results and discussion

### 3.1 Memory curves

Fig. 2 shows the dependencies $\overline{t_D} = f(\tau)$ (i.e. memory curves) for the gas tube filled with nitrogen at 4 mbar. The values of applied voltages are noted in the figure. Each dot in Fig. 2 is obtained as the mean value of 100 values. The shape of the dependencies $\overline{t_D} = f(\tau)$ are caused by various mechanisms, which lead to of secondary electron emission from the cathode. As can be seen from Fig. 2, the memory effect has not arrived up to 1000 for all values of applied voltages.

The memory curves can usually be divided into three regions [20]:

![Fig.1 Schematic diagram of the ECRP-DCMS system with a plasma source](image-url)
a. The plateau region, which exists for small values of relaxation times, from about 40 ms ($U_W = 700$ V), 50 ms ($U_W = 500$ V) and 70 ms ($U_W = 400$ V);

b. The increasing region, i.e. a region with increasing values of time delays with relaxation times; and
c. The saturation region.

For the plateau region, the standard deviations are smaller from correspond mean values for approximately one or two orders of magnitude. This is a consequence of the large concentration of positive ions in gas for small relaxation time. The positive ions originate in the gas and from the previous discharge, and they create an afterglow. The drift velocities of positive ions in the gases are very high, and consequently they reach the cathode very quickly. The positive ions create the secondary electrons when they impact the cathode. Because the high concentration of positive ions in gases for small relaxation time, the number of free secondary electrons in gases is also very high. These free electrons can cause electron avalanches, which lead to breakdown. As the concentration of free electrons increases, the time delay reaches very small values. It is necessary to note that for small values of relaxation times there is a high concentration of neutral active particles in the gas. However, their influences in secondary electron creation is almost insignificant.

![Figure 2](image)

**Fig. 2** Dependencies $f_D = f(\tau)$ (memory curves) for indicated applied voltages

As can be seen from Fig. 2, the increasing region of curve $f_D = f(\tau)$ begins with relaxation times greater than 40 ms ($U_W = 700$ V), 50 ms ($U_W = 500$ V) and 70 ms ($U_W = 400$ V). This part of the memory curve begins with a decreasing concentration of positive ion concentrations. Simultaneously with the decreasing concentration of positive ions, the metastable particles in the gas become dominant in breakdown initiations. The concentration of positive ions in the gas decreases very quickly, the number of secondary electrons decreases very quickly, and the time delay values rise very quickly (until approximately 100 ms, see Fig. 2). The concentration of metastable particles in the gas also decreases with an increase in the relaxation time. However, the concentrations of metastable particles in gas decrease slowly, and their role in initiation of secondary electrons from the cathode becomes more pronounced. Consequently, for relaxation time values greater than $\tau = 100$ ms, the region of quickly rising $t_D$ values is finished, and $t_D$ rises slowly. This slow decrease of $t_D$ with relaxation time is caused by the slowly decreasing number of $N(^4S)$ nitrogen atoms, which has an important role in breakdown initiation [21-23]. For these relaxation time values, the dominant mechanism of creations of initial electrons is deexcitation of metastable nitrogen atoms on cathode, which initiates secondary electron emission [24]. The decreasing concentration of metastable $N(^4S)$ nitrogen atoms is caused by recombination on the tube wall, electrodes, or in the gas. The slow decrease of concentrations of metastable atoms leads to a slow increase of the time delay values. Details of recombination processes are presented in Ref. [21].

The final, third part, of the memory curve is characterized by approximately constant values of time delay. As can be seen from Fig. 2, in our experiment these parts of the memory curves are not measured. This saturation of $t_D$ values is caused by the meaningful reduction of the number of neutral active particles in the gas. Consequently, the number of electrons, which is created in collision of neutral active particles to cathode, is strongly reduced. Thus, for these relaxation times, only cosmic rays can cause the electrical breakdown in gas. As the flux of cosmic rays varied during the measurement, the measured values of time delay varied [20].

### 3.2 Contributions of formative time and statistical time in total time delay

Fig. 3 presents the dependencies $D = f(\tau)$ (memory curves) and $\sigma = f(\tau)$, for voltages $U_W = 400$ V and $U_W = 700$ V (see Fig. 3(a) and $U_W = 500$ V (see Fig. 3(b)). As can be seen from this figure, for small $\tau$, the standard deviations are smaller in order for the mean values to be approximately one order of magnitude. The values of standard deviations rise slowly with the increase of the mean values. These regions correspond to the first part of the memory curves (ionic part), where the number of free electrons is very high. The large number of free electrons lead to very small statistical time delay values. The time delay values and their standard deviations are designated only with the values of formative time delay and their standard deviations. This is the main reason why the standard deviation of total time delay has two orders of magnitude smaller values than the corresponding mean values. The borders of this region for different applied voltages are $\tau = 70$ ms for applied voltages $U_W = 400$ V, $\tau = 50$ ms for $U_W = 500$ V and $\tau = 40$ ms for $U_W = 700$ V (see Fig. 3(a) and Fig. 3(b)).
As the relaxation times increase further, the standard deviation values increase and become comparable with mean values. The values of standard deviations are equal with the mean values for different applied voltages, which are $\tau = 80 - 90$ ms (for applied voltage 400 V), $\tau = 75$ ms (for 500 V) and $\tau = 70$ ms (for 700 V) (see Fig. 3(a) and Fig. 3(b)). The region of quickly rising time delay values ends. This indicates the recombination of all positive ions in cathode for these relaxation times, and relaxation time values when the standard deviation values become approximately equal with time delay values. This is characterized for exponential distributions. Then, the time delay is determined with statistical time delays. For these values of relaxation times, breakdown is initiated with neutral active particles.

### 3.3 Time delay distributions for different relaxation times

The time delay distributions for different relaxation times are shown in Figs. 4–8. The density distributions are presented with histograms, which are obtained using the rule that the modal class has about approximately 20% of all measured data. Histograms of relative frequencies are normalized to density distributions dividing by the class width $\Delta t_D$.

Together with density distributions, the time delay distributions are displayed in Gaussian and exponential probability scale (Laue diagrams). These distributions are obtained for voltages $U_W = 500$ V and each of them are obtained for 1000 independent and successive measurements.

The density distribution of time delay and the corresponding distributions in Gaussian probability scale for relaxation times $\tau = 3$ ms, $\tau = 15$ ms and $\tau = 40$ ms and applied voltage $U_W = 500$ V are presented in Fig. 4(a), Fig. 4(b) and Fig. 4(c), respectively. The density distributions of $t_D$ are fitted by Gaussian distributions and the distributions in the Gaussian probability scale are fitted by a straight line.

The regression coefficients are calculated for both fits, the regression coefficient $R$ for density distributions and $R^2$ for distributions in a Gaussian probability scale. The regression coefficients have values near one, which indicates their Gaussian shape. The Gaussian shape of the time distributions from Fig. 4, obtained for small relaxation times, indicates that the positive ions from the previous discharge have the main role in electrical breakdown initiation. Then, the values of the $t_S$ are much smaller from values of $t_F$. Consequently, the distributions of $t_F$ determine shapes of the distributions of $t_D$ [6]. The distributions for $\tau = 40$ ms (see Fig. 4(c)) have the only smaller regression coefficient, which indicated the losses the Gaussian shape in this case.
Fig. 4 The distributions of $t_D$ and Gaussian probability plot for voltage $U_W = 500$ V and indicated values of $\tau$

Figs. 5 and 6 show the distributions of time delay, for $\tau = 50$ ms and $\tau = 70$ ms, respectively. In both figures the distributions are shown in Gaussian probability scale (see Fig. 5(a) and Fig. 6(a)) and Laue diagram (see Fig. 5(b) and Fig. 6(b)). The trend of losses the Gaussian shape continues with greater values of $\tau$. This can be observed from the regression coefficients for Gaussian fits, and regression fits of diagrams in Gaussian probability scale (see Fig. 5(a) and Fig. 6(a)), which are smaller (these coefficients are: $R^2 = 0.97433$

and $R = 0.97612$ for $\tau = 50$ ms and $R^2 = 0.89875$ and $R = 0.9535$ for $\tau = 70$ ms). Simultaneously with the increasing Gaussian shape, the exponential shape becomes dominant. The exponential shape can be seen from Laue diagram in Fig. 5(b) and Fig. 6(b), which are fitted with straight lines. The corresponding regression coefficients in this case are: $R = -0.97079$ for $\tau = 50$ ms and $R = -0.99856$ for $\tau = 70$ ms. The regression coefficient for $\tau = 70$ ms is almost equal to 1, which indicated the exponential character of this distribution. The transitions from Gaussian

Fig. 5 The distributions of $t_D$, Gaussian probability plot and Laue diagram for $\tau = 50$ ms and $U_W = 500$ V

Fig. 6 Time delay distribution, Gaussian probability plot, and Laue diagram for $\tau = 70$ ms and $U_W = 500$ V
shape to exponential can be seen, and from density distribution for \( \tau = 70 \) ms, which is shown in Fig. 6(a). This density distribution is fitted with Gaussian and exponential distributions. The regression coefficient for Gaussian fit is \( R^2 = 0.89875 \), and for exponential fit is \( R^2 = 0.68597 \). However, the exponential fit is done and is excluded from the first class of histograms, and the regression coefficient is \( R^2 = 0.99146 \). This exclusion of the first class is reasonable because we seen the Laue diagram (see Fig. 6(b)). Values which correspond to the first class are only the small curvature of the Laue diagrams. As can be seen from the Gaussian probability plot for \( \tau = 70 \) ms (see Fig. 6(a)), dots begin for probability greater than 5\% and the straight line in this case does not present a Gaussian distribution.

This crossing of distribution shape from Gaussian to exponential is caused by contributions of \( t_S \) and \( t_F \) in total values of \( t_D \). With the increase of the \( \tau \) values, the number of positive ions from previous discharge decreases, and their role in breakdown initiation becomes smaller. Consequently, the contribution of \( t_F \) in total \( t_D \) is smaller with increasing the relaxation times. Simultaneously, the \( t_S \) becomes the main part in total \( t_D \). From Fig. 5 it can be concluded that for \( \tau = 70 \) ms, the \( t_S \) become main part in total \( t_D \).

In Fig. 8 the Laue diagram for relaxation times from \( \tau = 100 \) ms to \( \tau = 3 \) s (as indicated in figure) are given. The Laue diagrams are fitted with straight lines, and the corresponding regression coefficients are given in same figure. The regression coefficients which are presented in Fig. 7 and Fig. 8, indicate the exponential character of time delay distributions.

This exponential shape for greater \( \tau \) is a consequence of dominant contributions of \( t_S \) in total \( t_D \). This fact is caused by decreasing the concentration of positive ions that remain from the previous discharge, which have a main role in the breakdown initiation in gas for relaxation times \( \tau \leq 40 \) ms. Simultaneously, the influence of metastable particles in breakdown initiations increases and becomes the dominant mechanism in breakdown initiations for relaxation times \( \tau > 30 \) ms. Consequently, for \( \tau > 30 \) ms values of \( t_F \) become smaller and statistical time delay become dominant. The slow decreasing of metastable particle concentrations leads to the slow increase of the time delay values.

### 3.4 Time delay distributions for different applied voltages

The distributions of \( t_D \) for different values of \( U_W \) are investigated for: \( U_W = 400 \) V, \( U_W = 500 \) V and \( U_W = 700 \) V. These investigations are performed for different \( \tau \), when the distributions of \( t_D \) have different shape. These relaxation times values are: \( \tau = 15 \) ms, when shape of the distributions are Gaussian shape, \( \tau = 50 \) ms when their shape is between Gaussian and exponential and \( \tau = 70 \) s and \( \tau = 3 \) s, when their shape is exponential.

Fig. 9 shows the density distributions of \( t_D \) and the distributions in Gaussian probability scale, for \( \tau = 15 \) ms and applied voltages 700 V (see Fig. 9(a)), 500 V (see Fig. 9(b)) and 400 V (Fig. 9(c)). The histograms of density distributions are fitted with Gaussian distributions, and distributions in Gaussian probability scale are fitted with straight lines. The regression coefficients for all fits are given in each figure.
From the regression coefficients in Fig. 9, the Gaussian shape of distributions for all values of \( U_W \) can be seen. The Gaussian shape is least expressed for distributions obtained for \( U_W = 500 \) V and \( U_W = 400 \) V (see Fig. 9(b) and Fig. 9(c)).

The distributions of time delay, for \( \tau = 50 \) ms and different values of \( U_W \), are shown in Fig. 10. The relaxation time corresponds to the end of region when the positive ions have the dominant role in breakdown initiation, and begin the next region when the dominant role in the breakdown initiation has the both of positive ions and neutral active particles. The distributions of \( t_D \) lose the symmetrical shape (Gaussian shape), and become asymmetrical, in the correspond distributions for \( \tau = 15 \) ms. Consequently, from Fig. 10 it can be seen that the distributions are more symmetrical for greater values of voltages. This fact can be seen also from the indicated values of regression coefficients (regression coefficient tends from 0.97228 for 400 V up to 0.99613 for 700 V).

The greater regression coefficient for greater applied voltages is a consequence of better symmetry of distributions, i.e. the tendency of distribution shape to Gaussian. This suggests that the formative times have almost constant values with increasing the voltage. In contrast, the statistical time delay has smaller values with an increase of the voltage (from \( t_D = 239.5675 \mu s \) for 400 V until to \( t_D = 4.1353 \mu s \) for 700 V). The consequence of this is the greater part of \( t_F \) in \( t_D \), which leads to ore symmetrical distributions for greater voltages. Similar behavior was noted for Kr, where shows that the values of \( t_F \) is almost constant with increasing voltage, and become dominant part of \( t_D \) for higher voltage [12].

The further transition to exponential shape of time delay distributions can be seen from Fig. 11, where presents the time delay density distributions for \( \tau = 70 \) ms and different voltages (\( U_W = 400 \) V, \( U_W = 500 \) V and \( U_W = 700 \) V). As can be seen from Fig. 11 both of the fits, the Gaussian and exponential, are not well fitted to the time delay histograms. However, the exponential fits the dots (which correspond to the density distributions, without first class) very well. The losses the Gaussian shapes and tends to exponential can be seen from Fig. 12, which represents the Laue diagrams for voltages \( U_W = 400 \) V, \( U_W = 500 \) V and \( U_W = 700 \) V. These Laue diagrams can be well fitted with straight lines, with small deviations for little
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time delay values. However, these deviations cannot be well seen in Laue distributions. These deviations can only be seen from density distributions. These deviations can only influence small measured time delay values, and correspond to first class in histogram. These deviations are caused by formative time. For the smaller relaxation times, the formative time for $\tau = 70$ ms is smaller in $t_D$.

Finally for $\tau > 80$ ms, the distributions of $t_D$ have a sharp exponential shape, and the $t_s$ is the dominant part of $t_D$. This is a consequence of fact that the neutral active particles have a main role in breakdown initiation. As examples of these situations, in Fig. 13 the Laue diagrams for $\tau = 1$ s, and voltages $U_W = 400$ V, $U_W = 500$ V and $U_W = 700$ V are presented.

![Fig.11](image1.png)

**Fig.11** The distributions of $t_D$ for $\tau = 70$ ms and indicated values of $U_W$

![Fig.12](image2.png)

**Fig.12** Laue distributions for $\tau = 70$ ms and indicated values of $U_W$

![Fig.13](image3.png)

**Fig.13** Laue distributions for relaxation time $\tau=1$ s and indicated applied voltages

4 Conclusion

This paper has shown that different shapes of time delay distributions are correlated with different electrical breakdown mechanisms. These different breakdown mechanisms caused the different ratios of statistical and formative time delays, which are different for different experimental conditions (different $\tau$ and $U_W$). The distributions of $t_D$ are obtained on the basis of 1000 measurements for various overvoltages and relaxation times, for a gas tube filled with nitrogen at 4 mbar. The experimental distributions are fitted with Gaussian distributions for small values of relaxation time ($\tau \leq 40$ ms, for $U_W = 700$ V, $\tau \leq 50$ ms for $U_W = 500$ V and $\tau \leq 70$ ms for $U_W = 400$ V), and with exponential distributions for greater values of relaxation time ($\tau \geq 80 - 90$ ms for $U_W = 400$ V, $\tau \geq 75$ ms for $U_W = 500$ V and $\tau \geq 70$ ms for $U_W = 700$ V).

The shape of the time delay distributions strongly depends on the values of the relaxation times. For small relaxation time values, the gas has very high concentrations of free electrons, which is created from the impact of positive ions in the cathode. The high concentration of free electrons caused very small values of the statistical time delay, and consequently the formative time delay has become the dominant part of total time delay. In contrast, for greater values of the relaxation time, the concentrations of free electrons in gases are sufficiently smaller. For these relaxation times, the free electrons which initiate the breakdown are created from the de-excitation of neutral active states on the cathode. In these cases, the statistical time delay has values much higher than the formative time delay, i.e. the statistical time delay becomes the dominant part of total time delay.
The distributions for various voltages are determined by the ratio between the $t_S$ and $t_F$, and the fact that the values of the $t_F$ decrease much more slowly in order to $t_S$ with increasing the voltage. Consequently, for greater values of voltage and smaller values of relaxation time, the $t_F$ becomes the dominant part of $t_D$, and leads to much more symmetrical distributions for greater voltages. In contrast, for smaller values of voltages and greater values of relaxation time, $t_S$ becomes the dominant part of $t_D$, and the distributions become asymmetrical and tend to an exponential shape.

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