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Statistical time lags in AC discharges

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Abstract. The paper presents statistical time lags measured for breakdown events in near-atmospheric pressure argon and xenon. AC voltage at 100, 400 and 800 kHz was used to drive the breakdown processes, and the voltage amplitude slope was varied between 10 and 1280 V/ms. The values obtained for the statistical time lags are roughly between 1 and 150 ms. It is shown that the statistical time lags in AC-driven discharges follow the same general trends as the discharges driven by voltage of monotonous slope. In addition, the validity of the Cobine-Easton expression is tested at an alternating voltage form.

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1. Introduction

The breakdown process in gasses is a phenomenon that features gradual changes as the transition from the gaseous to the plasma state occurs. For a successful breakdown event it is necessary to supply the energy to the gas gap high enough to initiate electron avalanches; this is usually done by placing the gas gap in an electrode system, thus creating an electric field that gives energy to the free electrons in the gas. In high pressures and moderate to large electrode gaps, the breakdown process features a growth of thin, ionized channels. The development of the ionized channels is followed by the bridging of the electrode gap, building up the channel conductivity and finally a sharp drop of the potential difference between the electrodes. This point in time is known as the breakdown moment. The potential difference across the gas gap associated with the breakdown moment is called the breakdown voltage.

The duration of the breakdown process, starting from the first electron multiplication that will lead to breakdown until the breakdown moment, is called formative time lag. Ideally, the breakdown process in the gas starts at the exact same moment at which a sufficiently high electric field is brought to the gas gap. However, this

would require an abundance of free electrons in the gas gap, to ensure that at least one of them would start an electron avalanche that would lead to breakdown. In reality, there is a delay between the onset of the electric field and the start of the formation process, due to the absence of free electrons in the area of adequate electric field strength. This delay is called the statistical time lag. The statistical time lag comprises of two main parts: the time spent on waiting for a free electron to appear in the electrode gap and the time it takes to start an avalanche process that will lead to breakdown.

Formative time lags have been examined for pulsed breakdown processes in low pressure and for a number of gasses [1,2], as a function of the overvoltage and experiment repetition frequency or the afterglow period. It was found that the decrease in the overvoltage used to drive the breakdown process causes an increase in the formative time lag. This is due to the specific form of the Townsend's first ionization coefficient α as a function of the reduced electric field E/p [3]

$$\alpha/p = A \exp(-Bp/E) \quad (1)$$

A and B are coefficients specific for the gas type. The ionization coefficient is a steep function of the reduced electric field and the amplification of the number of electrons in an avalanche exponentially rises with α [3]. Already a very small increase of the reduced electric field above the threshold value is thus sufficient for a large reduction of the formative time lag.

The experimental studies of statistical time lags have been conducted in a broader set of conditions than the considerations on the formative lag, but still by and large in low gas pressures [4–9]. It has been observed that the increase in the overvoltage applied across the gas gap causes a decrease in the statistical time lag. This means that the number of electrons required to start a successful breakdown process decreases with the increase of the reduced electric field in the gas gap. It also shows that one electron is not always sufficient to start a successful breakdown process, otherwise the statistical time lag would be independent of the overvoltage. This result was anticipated by Wijsman [10] in 1949. He developed an analytical formulation of the probability $P(n, d)$ that one electron causes an avalanche of n electrons at distance d from the electrode

$$P(n, d) \approx (1/\bar{n}) \exp(-n/\bar{n}) \quad (2)$$

$$\bar{n} = \exp \left(\int_0^d \alpha(x) dx \right)$$

This probability is exponentially decreasing with the number of electrons in the avalanche n . He also gave a probability P_0 that the succession of avalanches goes indefinitely, i.e. that the avalanche will lead to breakdown

$$P_0 = \begin{cases} 0 & , q < 1 \\ 1 - 1/q & , q > 1 \end{cases} \quad (3)$$

$$q = \gamma(\bar{n} - 1)$$

γ is the secondary electron emission coefficient for ions in the breakdown process. If one wishes to determine the probability of breakdown as a function of the applied voltage,

one should know q as a function of the voltage. In general, q increases rapidly with the reduced electric field in the region above the breakdown value, again due to the specific form of the Townsend's first ionization coefficient as presented in equation 1. As a result, the statistical time lag indeed decreases very quickly with just a small increase in the electric field in the gas gap.

It has also been shown from the experiments varying the afterglow time, that the statistical time lag depends on the amount of pre-ionization. The more charged particles remain from the previous discharge, the shorter the statistical time lag. Related to this, the presence of UV irradiation or radioactive materials were observed to have a decreasing effect on the statistical time lag with the increase of the gas gap length because of the increased probability of the appearance of an electron to initiate the discharge [4].

Zuber and von Laue developed a theory in 1925 [11, 12] that deals with the structure of the total time lag. The theory involves several parameters important for the characterization of the time lag, such as the rate at which the electrons are produced in the gap by an external ionizing agent β , the probability of an electron appearing in a region of the gas gap where it can start an avalanche p_1 and the probability that such an electron will indeed lead to a spark p_2 . The number of sparks that occur in the time interval $t + dt$ is

$$dn = -\beta p_1 p_2 n_t dt \quad (4)$$

n_t is the number of sparks with time lags greater than t . Integration over the whole time interval $[0, t]$ gives

$$\ln(n_t/n_0) = -\int_0^t \beta p_1 p_2 dt \quad (5)$$

n_0 is the total number of time lags observed. Assuming that parameters β , p_1 and p_2 do not change with time, the equation above can be expressed as

$$n_t = n_0 \exp(-\beta p_1 p_2 t) = n_0 \exp(-t/\sigma) \quad (6)$$

According to the statistical theory, σ is the mean time lag, although it can be easily approximated to the mean statistical time lag, providing that the formative lag in the experiment is small enough compared to the total time lag.

The work of Zuber and von Laue has been proven to be valid in a number of experiments, but its limitation lies in the fact that the parameters β , p_1 and p_2 are presumed to be constant in time. When voltage is varied in time, these coefficients vary with it. It has been experimentally determined by Cobine and Easton [13] that the equation 6 can best be modified in the following empirically obtained form

$$n_t = n_0 \exp(-bt^c) \quad (7)$$

The parameter c can be more or less than unity, depending on the trend of the voltage across the electrodes. For example, if the voltage is decreasing, c will be less than unity. This has been explained in the following way: the longer the time lag, the lower the voltage across the gap when a free electron appears in the volume. This causes a lower

probability that the electron will lead to breakdown. As a result, an electron arriving late is less likely to cause breakdown than the electron arriving early in the experiment. Therefore, a greater number of the time lags fall in the long time range than would be the case at a constant voltage. If the voltage across the gas gap would happen to increase during the experiment, the result would be the opposite, c would be greater than one.

We took a particular interest in the statistical time lags in high pressure argon and xenon discharges for their importance in the lighting industry. While the formative lag is of the order of microseconds or less in high intensity discharge (HID) systems [2, 14], the statistical lag can be orders of magnitude larger and have a large spread of values. This is of particular interest for lamp driver design.

In this paper we show the measured values of the statistical lag as a function of the gas type and pressure, electrode gap, frequency and voltage amplitude slope for high frequency AC breakdown in argon and xenon. We also test the validity of the theory presented by Zuber and von Laue [11, 12] and later adapted by Cobine and Easton [13], on the structure of the time lags during breakdown in gasses. We show that their theories, although developed for quite different voltage forms, are still general enough to hold for high-frequency AC breakdown, provided that one additional parameter is introduced.

2. Details of the experiments and the analysis

2.1. Experimental parameters

Table 1. Lamp types used in the experiments. A lamp type is one specific combination of gas type, pressure and electrode gap.

Gas	Pressure [bar]	Electrode gap [mm]	number of available lamps
Ar	0.3	4	6
		7	5
	0.7	4	3
		7	5
Xe	0.3	4	3
		7	2
	0.7	4	3
		7	3

Setup details were given in [14] and will be shortly presented in this section. We used a pin-pin electrode geometry enclosed in 70 W Philips YAG (Yttrium Aluminium

Garnet) burners as designed for metal-halide HID lamps. The electrodes were rod-shaped and 0.6 mm in diameter, forming an electrode gap of 4 or 7 mm. The volume of the lamp burners we used was $3.6 \times 10^{-7} \text{ m}^3$. They were filled with 0.3 or 0.7 bar of argon or xenon, without the addition of salts or mercury.

The experiments were done using a high-frequency sine voltage signal of linearly rising amplitude on the active electrode, while the second electrode was grounded. The AC signal was generated in a way which allowed us to change the frequency between 100 kHz and 1 MHz and the slope of the voltage amplitude between 10 and 1280 V/ms. We performed breakdown voltage measurements for each breakdown process, using a high voltage probe and an oscilloscope. Breakdown voltages were measured for different frequencies and voltage amplitude slopes.

We have made and measured several lamps for each type (*lamp type* in this case denotes a single combination of gas type, gas pressure and electrode gap) to avoid our measurements being influenced by possible defects in electrodes or burners or errors in lamp filling or sealing procedure. The list of lamp types used in the experiments is given in table 1. Ten breakdown voltage measurements were performed for each lamp in table 1 and for each data point. One data point is a specific combination of the voltage frequency and the slope of the voltage amplitude. The average values and the standard deviations were calculated for each lamp, and subsequently for each lamp type. The data points in the graphs throughout this paper represent the average values and the standard deviations for the corresponding lamp type.

The experiment repetition frequency was held constant at 0.1 Hz. This choice provided sufficient time between two breakdown processes for them not to influence each other. Our experimental systems contained only noble gasses and the discharges were not allowed to burn after breakdown, which ensured that no gas heating would take place. A current limiter was used to ensure that the power to the lamps is cut off after breakdown [14]. The dielectric surface of the lamp burner in which we have enclosed our experimental system was, however, very likely to have been charged during one breakdown process and still remained charged during the next one, due to the very long decay time of charge on dielectric surfaces. However, we found this to be an acceptable starting condition, for two reasons. First, the discharges in our geometry do not develop on the burner surfaces, as has been shown previously [14]. The charges on the surfaces are, thus, not actively participating in the discharge development. Second, the starting conditions were the same for each breakdown event, or similar to the point that we could not distinguish one from another. We know this because during the measurements we did not observe a systematic change in the breakdown voltage. Large changes in the amount of free electrons in the gas volume where the electric field was high enough to sustain an avalanche process would have changed the outcome of the breakdown voltage measurements. Even if the changes of the surface charge were gradual, the breakdown voltages would gradually change over time. Nothing similar was observed.

The breakdown processes were at times aided by a flux of UV irradiation at 254 nm. Between 10^{13} and 10^{14} photons entered the lamp volume every second, and about 5%

of those hit one of the electrodes. With the estimated efficiency of 10^{-3} for photoeffect on the cathode [3], the UV irradiation ensured the emergence of between 5×10^8 and 5×10^9 electrons per second in the lamp volume. Consequently, the preionization levels were high enough to minimize the statistical time lag, the assumption which will be later supported in the results section of the paper. Another function of UV irradiation in these experiments was to clean the charge off the surfaces of the lamp burner. This effect has been discussed already in 1981 [15]. The lack of charge on the burner surfaces in the case of UV-assisted breakdown is an essential difference between the UV-aided and non-aided breakdown events in the case where the discharges develop on the insulating surfaces. However, as the discharges in our experiments did not develop on the dielectric surfaces [14], this effect is not considered important.

2.2. Determination of statistical time lags

Figure 1. Schematics of the time lag structure. The figure shows the voltage on the active electrode, depicts the concept of breakdown moment and breakdown voltage. The voltage signal is divided into three sections, further explained in the text. The length of the three sections is not in scale in the figure, as section 1 takes a much bigger part of the voltage signal in reality. In addition, section 2 is larger compared to section 3 than shown in the figure. Threshold voltage mentioned in the text is the voltage amplitude at the transition from part 1 to part 2.

The procedure of determining the statistical time lag in AC breakdown required the comparison of breakdown voltage of non-assisted and the UV-aided breakdown processes. The idea is illustrated in figure 1. The experiments we performed were done by using sine voltage of linearly rising amplitude. In the first part of the voltage signal, denoted as 1 in the figure, the voltage was too low to start an electron avalanche in the lamp. At the transition from part 1 to part 2, the voltage crossed the threshold at which the reduced electric field in areas of the lamp became high enough for an electron avalanche to start. At this point it became possible for the discharge to start forming near the electrode tips and subsequently lead to breakdown. However, the

preionization levels in non-aided breakdown events were very low, which caused an appreciable statistical time lag to occur, while the voltage amplitude was still rising in a linear way. This portion of the breakdown process is denoted as 2 in the figure. Finally, at the transition from part 2 to part 3, an avalanche started that later lead to breakdown. The final part of the process is therefore the formative time lag.

The influence of UV irradiation on the breakdown process was already discussed at length in [14]. It was concluded that there were two effects expected to have a notable influence on the breakdown process. One, the statistical time lag in UV-assisted measurements was expected to be negligible. Therefore, the part 2 in the voltage form shown in figure 1 does not exist for the UV-aided breakdown. The formation of the avalanches that will lead to breakdown take place after the voltage amplitude crosses the threshold value for sustaining the breakdown process. This is why the UV-aided breakdown takes place at lower voltages, which leads us to the second UV-related effect with notable influence on the breakdown process. The formative time lag was expected to be prolonged because the breakdown process took place at lower voltage. We will show that even the prolonged formative time lag in UV-aided breakdown processes as measured and reported in [14] is still orders of magnitude lower than the statistical time lag encountered in the non-aided case, and can be neglected in the calculations.

As stated before, by comparing the breakdown voltages of UV-aided and non-aided breakdown processes for the same frequency and voltage amplitude slope, we can derive the statistical time lag in the non-aided breakdown events. Let T_0 refer to the time interval denoted as part 1 in the figure 1, when the electric field in the gap is too low to sustain a breakdown process. T_f is the formative time lag, and refers to the part 3 of the breakdown process as represented graphically in figure 1. Let the formative times in UV-assisted case be denoted as $T_{f,UV}$. The statistical time lag T_s is presumably present only in non-assisted breakdown. The structure of the total time used for one breakdown event for non-assisted (T_{tot}) and UV-assisted ($T_{tot,UV}$) events can be represented in the following way

$$T_{tot} = T_0 + T_s + T_f \quad (8)$$

$$T_{tot,UV} = T_0 + T_{f,UV} \quad (9)$$

The difference in the total time can give the statistical time lag, presuming that the difference in the formative times can be neglected when compared to the statistical lag, $T_s \gg T_{f,UV} - T_f$

$$T_{tot} - T_{tot,UV} = T_s + (T_f - T_{f,UV}) \approx T_s \quad (10)$$

The total time can be expressed as the ratio between the breakdown voltage V_{bd} and the slope of the voltage amplitude R

$$T_{tot} = V_{bd}/R \quad (11)$$

The statistical time lag can be expressed as a function of slope and voltage difference

$$T_s = \frac{V_{bd} - V_{bd,UV}}{R}. \quad (12)$$

3. Results and discussion

3.1. Breakdown voltage measurements

Figure 2. Breakdown voltage measured as a function of the voltage amplitude slope, in UV-assisted and non-assisted breakdown events. The data shown belongs to the discharges in argon, at 0.7 bar and at 400 kHz. The inset shows the same data, only on a logarithmic x -axis. The same trends as shown in this graph were obtained at other gas pressures, frequencies and also for xenon.

Figure 2 shows the structure of the measurements used to calculate statistical lag in AC-driven breakdown processes. We compared the breakdown voltage measurements for UV-assisted and non-assisted breakdown processes and calculated the time lags from the difference in the breakdown voltages measured at the same frequency and the same voltage amplitude slope. For these calculations to be valid it is necessary to assume that the UV-assisted breakdown is virtually free of statistical lag and that the UV irradiation does not affect the discharge evolution in any other way.

The effects the UV irradiation has on a growing discharge in our experimental conditions have already been discussed in [14] and in the previous two sections. Our conclusions were that the main effect is the significant lowering of the statistical time lag. Figure 2 shows that the statistical time lag is not only lowered, but virtually gone in the case of UV-aided events, by demonstrating the difference in behaviour of the breakdown voltage as a function of the voltage amplitude slope. When the breakdown process was aided by UV irradiation, the breakdown voltage did not change with the slope, which was not the case with the non-aided breakdown events.

The link between the observed phenomenon and the assumption about the lack of the statistical time lag in UV-aided processes follows from figure 1. There, a portion of the voltage signal at the active electrode in the non-aided case is inefficiently used to wait for an electron avalanche that will subsequently develop into a full discharge. This part is designated as region 2 in the figure and causes statistical time lag. During this time the voltage amplitude keeps rising, due to its positive slope. The faster the slope,

the more the voltage amplitude rises in the same amount of time. In an event where a breakdown process would not suffer from statistical time lag and where the formative time lag would be negligible, the measured breakdown voltage would be the threshold voltage amplitude needed for breakdown and the breakdown voltage would not change with the amplitude slope.

The contribution of the formative time lag to the increase of the breakdown voltage would be important in the case where the formative time lag would be large or in the case of fast voltage amplitude slopes. Formative time lags in our experiments were, however, very short. As shown in [14], formative times rise with the increase in the voltage frequency. The longest formative times relevant to the calculations presented in this paper were in argon at 0.7 bar and 7 mm electrode gap at 800 kHz, xenon at 0.3 bar and 7 mm electrode gap at the same frequency and xenon at 0.7 bar and 7 mm electrode gap at 400 kHz. The formative times for these discharges were 0.041 ms, 0.121 ms and 0.037 ms, respectively, for UV-aided breakdown. We take the values for the UV-assisted events as a reference because these formative times are expected to be longer than the corresponding formative time lags in non-assisted breakdown processes because they occur at lower voltage [14]. At the highest voltage amplitude slopes at which the statistical time lags were calculated, the increase in voltage due to the formative time lags was 26 V, 39 V and 47 V, respectively. Such small increases in voltage fall within the error bars of the breakdown voltage measurements. In addition, all formative time lags were at least one to two orders of magnitude lower than the corresponding statistical time lags, which will be presented in the next section. The values were measured as the time delay from the first light emitted from the electrode tip to the breakdown moment. Even if the formation time took twice as long, the formative time lags would still be small enough to be neglected in comparison with the statistical time lags.

In conclusion, our measurements have shown that the UV-aided processes were virtually free of statistical time lag, that the UV irradiation did not affect the discharge development in a way that would disallow us to compare the UV-aided and non-aided breakdown events [14] and that the formative time lags were negligible compared to the corresponding statistical time lags [14]. Consequently, the assumptions on which rests the validity of the procedure for determining statistical time lag as described in section 2.2 are satisfied for AC-driven breakdown events in our experimental conditions.

3.2. Statistical time lags

Figures 3 to 8 show the statistical time lags as a function of voltage amplitude slope, calculated at 100, 400 and 800 kHz. The bars in the graphs represent the standard deviation calculated for a function of multiple (two in our case) independent variables where each variable has a known variance.

The term *overvoltage* is used quite often in this paper. It is associated with the excess voltage applied to the electrode, with respect to the threshold breakdown voltage at given conditions. If the threshold breakdown voltage is given by V_b , and the voltage

Figure 3. Statistical time lags for argon at 100 kHz, presented as a function of voltage amplitude slope.

Figure 4. Statistical time lags for xenon at 100 kHz, presented as a function of voltage amplitude slope. The measurements of breakdown properties in 0.7 bar xenon could not be performed due to the limitations of the equipment.

at which the measurements are performed is $V_b + \Delta V$, than the ΔV is the overvoltage applied to the electrode.

It is usual [1,2,4–9] to show time lags as a function of overvoltage, not of the slope of the voltage amplitude. It is also easier to relate the statistical time lag to voltage or electric field than to the voltage amplitude slope, because it is intuitively clear that the higher the electric field, the higher the probability that one electron will cause avalanches that will lead to breakdown [10]. We chose to present our results as a function of the voltage amplitude slope because the voltage amplitude slope is a parameter which we

Figure 5. Statistical time lags for argon at 400 kHz, presented as a function of voltage amplitude slope.

Figure 6. Statistical time lags for xenon at 400 kHz, presented as a function of voltage amplitude slope.

were able to control very precisely in our experiments. In addition, even though the slope can be related to the overvoltage in a simple way, the interpretation of the results is not straightforward. Because of the reasons given, all the determined statistical time lags are presented as a function of the voltage amplitude slope, and the extension to the scope of overvoltage is presented in the next section.

Figures 3 to 8 show that the statistical time lag decreases as a steep function of the voltage amplitude slope. This is caused by different levels of overvoltage achieved at different voltage amplitude slopes during statistical time lags. The faster the slope, the more the voltage amplitude grows in a given time increment. The resulting overvoltage

Figure 7. Statistical time lags for argon at 800 kHz, presented as a function of voltage amplitude slope.

Figure 8. Statistical time lags for xenon at 800 kHz, presented as a function of voltage amplitude slope. The measurements of breakdown properties in 0.7 bar xenon and with 4 mm electrode gap could not be performed due to the limitations of the equipment.

is higher for the faster rising voltage. Higher overvoltage causes a higher Townsend's first ionization coefficient and results in more efficient electron avalanches. The probability of a successful breakdown greatly increases with the number of free electrons available in the electrode gap. This is a crucial factor in the behaviour of the statistical time lags, as we have discussed in the introductory section.

Statistical time lag in all the given figures is always bigger in breakdown events at higher gas pressure and in xenon compared to the breakdown events in argon. The time lags do not appear to be a function of frequency. This is a result one would expect given

that there is no transition between the drift-dominated to the diffusion-dominated mode in our experimental conditions, as we have shown in [14,16]. With further increase in frequency we would expect the statistical time lag to be lowered, as the electron loss processes become lower and diffusion-dominated.

The statistical time lags reaching 120 ms for the slowest slope (Ar at 0.7 bar and 4 mm electrode gap) are quite large compared to the values obtained for pulsed discharges [4]. However, given our slow voltage amplitude slope and the fact that we performed the measurements using high frequency AC voltage, we expected lower electric fields in the electrode gap and consequently larger statistical time lags.

A more interesting observation is that the statistical lag in shorter electrode gaps is larger than the corresponding lag in the larger gaps. As was explained in [4], increasing the gap length allows many more electrons to be produced in the gap by means of cosmic radiation or similar events responsible for the occurrence of first free electrons; this, in turn, reduces time lags. The effects are very clear for the difference in electrode gaps used in our experiments - reducing the gap from 7 mm to 4 mm effectively reduces the volume where the initial electrons have to be created by 50%.

3.3. Statistical time lags as a function of overvoltage

Figure 9. Statistical time lags for argon discharges at 100 kHz, presented as a function of overvoltage at the end of the breakdown process.

Time lags in general are usually presented as a function of overvoltage, which is understandable given the fact that they can be related to the Townsend's first ionization coefficient, whose value depends greatly on the imposed electric field. Mean statistical time lag can be expressed [4,5] as

$$\bar{T}_s = \frac{1}{YP}. \quad (13)$$

Figure 10. Townsend's first ionization coefficient α calculated as a function of time for different voltage amplitude slope. The data belonging to argon discharges at 0.7 bar, 4 mm electrode gap at 100 kHz were used for calculations. See the text for more details.

Y is the electron yield, and P is the probability that one electron will cause avalanches that will lead to breakdown. P was given in the introductory section in equation 3. This equation holds for low pressure discharges and in cases where the formative time lag is much smaller than the statistical time lag. While the latter condition was fulfilled in our experiments, we were dealing with the discharges in high pressures, which makes deviations from the theoretical predictions possible.

It is not simple to express the statistical time lags as a function of overvoltage in our experiments for the simple reason that the overvoltage was changing during the statistical lag. One should recall that we were doing experiments with voltage amplitude rising in time and a sine voltage signal. Nevertheless, time lags can be expressed as a function of the final overvoltage reached at the end of the breakdown process, as presented in figure 9.

The figure shows statistical time lags for argon discharges at 100 kHz. The overvoltage was calculated in the following way

$$OV = \frac{V_{bd} - V_{bd,UV}}{V_{bd,UV}}. \quad (14)$$

Large error bars in x direction are a consequence of large statistical spread of breakdown voltages in non-aided breakdown events, as shown in figure 2.

The data in figure 9 can be fitted to a double exponential function of the form

$$\bar{T}_s = ae^{-be^{-c/OV}}. \quad (15)$$

The same is true for the data obtained at two other frequencies and for breakdown in xenon. The large range of values of the coefficients a , b and c that can be used in the fitting procedure makes it inappropriate to ascribe a high degree of certainty to any

theory trying to explain these measurements. A good fit can be made with c ranging from 1 to 10^{20} . Coefficients a and b cannot be chosen in such a wide range of values, their values are typically limited within one or two orders of magnitude.

Still, we would like to comment on the possible origin of the double-exponent dependency on the overvoltage. Equation 13 shows that in principle, the statistical time lag is a function of two parameters. Combining equations 13 and 3 shows that the mean statistical time lag is proportional to

$$\bar{T}_s \propto \frac{1}{Y\gamma(\exp(\alpha d) - 1)}. \quad (16)$$

The electron yield Y is difficult to deduce, since there are numerous theories explaining breakdown in high pressures [4] and we are working in an AC regime, where electron production and loss happens on a larger time scale than in typical pulsed discharge [14, 16]. However, if we assume an exponential evolution as a function of α , as is so often seen in the literature [4], the mean statistical lag becomes proportional to

$$\bar{T}_s \propto \frac{1}{\gamma \exp(\alpha d)(\exp(\alpha d) - 1)}. \quad (17)$$

Assuming that $\exp(\alpha d) \gg 1$ leaves us with the exponential function in the denominator. With the form of Townsend's first ionization coefficient as given in equation 1, equation 17 can be rewritten as following, for a single value of the electric field

$$\bar{T}_s \propto \gamma(e^{-2Apde^{-Bp/E}}). \quad (18)$$

The electric field is presumably a linear function of the applied voltage. Therefore, it is a linear function of the overvoltage, and we can assume $E = E_0 + E_1$, where E_0 is the threshold electric field needed for breakdown and E_1 is the excess electric field that is present in the experiments. The coefficients A and B depend on the gas type.

The reasoning described above can be considered valid for discharges at a constant overvoltage. In our experiments the voltage amplitude slope was positive, and we were working with AC voltage signal. The overvoltage was not constant. However, one should look more closely to the parameter α , which is a steep function of the electric field [3].

Consequently, α at voltage extremes is a steep function of time in our experiments. Figure 10 shows its evolution as a function of time for the voltage amplitude slopes used in our experiments. The calculations for this figure were done with parameters $A = 12 \text{ cm}^{-1}\text{Torr}^{-1}$ and $B = 180 \text{ Vcm}^{-1}\text{Torr}^{-1}$ [3], for 0.7 bar argon discharge in a homogenous electrode gap of 4 mm. We used a simple expression for the electric field in a homogenous electrode gap, thus underestimating the electric field in the experiments. Our purpose was, however, only to demonstrate the behaviour of α with time. Time zero on the x -axis designates the moment where the voltage passed the threshold value needed for breakdown - effectively, the x -axis shows the statistical time lag in the experiments.

The behaviour of α with time and electric field suggests that a small change in the experimental conditions or timing causes a big change in α , and consequently in the values of P and Y in expression 13. If the biggest contribution is also the one governing

the final value of P and Y , we can say that these parameters and the mean statistical time lag are local functions of electric field, both in time and in space. We expect this to be the reason why a theory valid only for homogenous electric fields constant in time can also be applied to our case.

3.4. The Cobine-Easton expression

Figure 11. The data on statistical time lags belonging to argon at 0.3 bar and 7 mm electrode gap, at 400 kHz. The data is presented in accordance with the Cobine-Easton relation. Further details can be found in the text.

The theory on the structure of time lags by von Laue and Zuber was published in 1925 [11,12] and corrected in 1943 by Cobine and Easton [13]. As we have described in the introductory section, the theory was conceived to describe breakdown in DC voltage conditions. However, it was developed in a way that did not explicitly make use of the DC voltage form. The theory of von Laue and Zuber uses the spread of time lags in the experiments to determine the mean time lag σ , as shown in equation 6. According to their theory, sigma is given by the production rate of electrons by an external ionizing agent β , the probability that an electron will appear in the part of the gas gap where it can lead to breakdown p_1 and the probability that the electron in question will indeed lead to breakdown p_2 . These probabilities should not be a function of time.

$$\sigma = 1/\beta p_1 p_2. \quad (19)$$

As we were working with AC voltage, these three probabilities were not sufficient to describe our system. One more parameter was always important, and that was the phase in the voltage cycle in which an electron would appear in the electrode gap. The electric fields that governed the breakdown processes in our experiments were the ones at the voltage cycle extremes, as we were working with voltage amplitudes that were not high above the threshold values. Therefore, if an electron would appear in the electrode gap at a moment when the voltage phase was far from an extreme, chances of this electron

to cause an electron avalanche would be very small. This additional parameter, the probability that the electron would appear in the electrode gap at a favourable voltage phase, can be denoted as p_{AC} . The aforementioned equation can now be rewritten as following

$$\sigma = 1/\beta p_1 p_2 p_{AC}. \quad (20)$$

This holds only for constant electric fields, or in our case, for the electric fields with amplitudes that are constant in time.

Cobine and Easton have shown that for voltage that is not constant in time, a slight modification should be made, as in equation 7. This modification comes from the fact that for breakdown events in which voltage with slope different than zero is applied, the probabilities p_1 and p_2 are a function of voltage and therefore a function of time. Our addition p_{AC} is also a function of the voltage amplitude.

The new form the von Laue - Zuber expression 6 takes is shown in equation 7. It contains the parameter b in the exponent, which has to have the dimension of $[\text{time}]^{-c}$. However, we do not know how the probabilities p_1 , p_2 and p_{AC} develop with time, and we cannot calculate the mean statistical time lags as a consequence.

From our experiments can be deduced that the theory of Cobine and Easton can in principle be applied to AC-driven breakdown processes as well as DC. Figure 11 shows a $\log(\ln)$ -log plot of the number of breakdown events with the time lag greater than t , as a function of t . According to equation 7, this plot should give a linear curve for each combination of experimental parameters (frequency, slope, lamp type).

$$\begin{aligned} \ln(n_0/n_t) &= bt^c \\ \log(\ln(n_0/n_t)) &= \log(b) + c \log(t) \end{aligned} \quad (21)$$

Figure 11 shows that the data obtained in the experiments indeed forms sets that can be approximated by linear curves. One should notice that the shapes of the plots greatly depend on the amount of the data points that we have available, because the ordinate axis basically shows the ratio of the number of the events that fulfill certain condition and the total number of events. When observing various plots of this type, we have noticed that the linearity indeed improves with the number of data points.

4. Conclusions

In this paper, we have presented the statistical time lag measurements for AC-driven breakdown events, using a slow voltage amplitude slope. Voltage frequency used in the experiments ranged from 100 to 800 kHz and the electrode gap was either 4 or 7 mm.

The statistical time lags varied between roughly 1 and 150 ms, depending on the gas type, pressure, electrode gap and the voltage amplitude slope. The statistical time lag was greater in xenon than in argon, at higher pressure and smaller electrode gap, which was explained by a smaller number of free electrons available at a given moment in the gas volume.

The statistical time lags were presented as a function of the voltage amplitude slope and as a function of overvoltage. A double-exponential function fit was made to the statistical time lags as a function of overvoltage. We suggest this to be the result of specific forms of the mean statistical time lag as a function of Townsend's first ionization coefficient.

Finally, we have shown that the theory presented in 1943 by Cobine and Easton [13] for breakdown events driven by long square pulses is general enough to show the expected results in the case of AC-driven discharges as well. Further research is needed to examine the extent of validity of this theory in the AC case.

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