Structure pattern peculiarities and electrical characteristics of surface dielectric barrier discharge in air driven by impulse and sine high voltage

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Abstract. Structure patterns and electric characteristics of surface dielectric barrier discharges in air driven by periodic unipolar impulse voltage with ns front duration and sine voltage of the same frequency \( f = 15 \text{ kHz} \) are presented. An influence of voltage impulse polarity, amplitude and impulse duration on discharge characteristics is shown to exist. The currents extracted from the surface discharge plasma layer by d.c. voltage of additional third electrode are found to depend on the waveform of the applied high voltage impulses.

1. Introduction

It has been shown in a range of works that waveform of the supply voltage is a crucial parameter for non-thermal atmospheric pressure barrier discharges which are relevant for a variety of applications [1-2]. Another prominent example of the generation of non-thermal plasmas are surface dielectric barrier discharges (SDBDs) [3]. Although SDBDs are commonly sine-driven it has been shown experimentally [4] that pulsed operation enables in a range of applications a higher yield of different species, lower power consumption and allows the study of variable HV parameters that define the discharge characteristics. The results of experimental investigation of pulsed driven SDBD can be used in modeling of the surface discharges for different conditions.

The aim of the present work was to find the main factors that define the SDBD structure for different characteristics of the applied voltage: different impulse amplitude, different polarity and impulse duration and sine voltage of the same frequency – and connect the structure peculiarities with electrical characteristics of SDBD and the yield of produced charged species.

2. Experimental set-up

The experimental set-up with apparatus for diagnostics is schematically presented in Fig. 1. The single strip arrangement featured a double-sided dielectric barrier configuration. An Alumina plate 1 mm of thickness and permittivity \( \varepsilon_r = 9.5 \) was used as a barrier, the HV electrode (1) placed on one side of the barrier was a Nickel strip (14x80 mm) 30 µm thick all edges of which were covered with an epoxy layer to prevent discharge appearance. The main electrode with the discharge (2) was a Nickel strip 1 mm wide, 80 mm long and 30 µm thick placed on the reverse side of the barrier and grounded through a specially made fast current active low inductance probe (\( R_{pr} = 7.8 \text{ Ohm} \), rise time 25 ns).
< 2 ns). High voltage measurements were performed by voltage probe (Tektronix P6015, rise time 4.67 ns). A third flat electrode (3) (40x60 mm) which was used in a three-electrode arrangement was placed at a distance 1 cm from the plasma layer of the discharge. This electrode having DC high potential (up to 10 kV) was used to measure the current of charged species produced by SDBDs. The three-electrode arrangement was housed in a dielectric sell with Plexiglas windows. A flow of dried air (1.7 l/min, humidity λ < 1%) was maintained through the sell along the strip with the discharge. The discharge in the two-electrode arrangement exposed to the high-speed camera measurements was maintained in a weak blowing of open atmospheric air. The blowing was needed to carry away the ozone from the discharge. The pulsed surface discharge was driven by unipolar square wave periodic pulses of different polarity with \( U_m = 7 \) and 8 kV and \( f = 15 \) kHz (\( T = 67 \) µs) using a specially developed generator [5]. The pulse width was varied from 0.5 µs to 45 µs. Most measurements were carried out with a HV slope steepness of the voltage impulse equal to 70-80 V ns\(^{-1}\) which supported a rise/fall time of 130 ns. The sinusoidal surface discharge was driven by high voltage using a special sine generator with fixed frequency \( f = 15 \) kHz and voltage amplitude \( 2U_m = U_{pp} = 6 \) kV.

The optical diagnostic consisted of ultrahigh-speed camera Phantom v2511 and a photo-camera Nikon D5200.

![Fig. 1. The experimental set-up. A – scheme for registration of discharge structure, B – scheme for registration of extracted current](image)

**3. Experimental results and discussion**

The pictures of the discharge structure made by speed camera (time exposure 17 µs) are shown in Fig. 2 for rising (A and C) and for falling (B and D) slope of positive and negative impulse voltage. Fig. 2 also presents corresponding oscillograms of voltage impulse and electrical discharge current \( I_{dis} = I_{tot} - I_{displ} \).

| Positive voltage | Negative voltage |
|------------------|------------------|
| ![Positive voltage image](image) | ![Negative voltage image](image) |

![Current vs voltage oscillogram](image)

![Current vs voltage oscillogram](image)

![Current vs voltage oscillogram](image)

![Current vs voltage oscillogram](image)
**A** | **B** | **C** | **D**
---|---|---|---

*Fig. 2. Discharge structure and corresponding voltage and current curves for different voltage impulse polarity, $U_m = 8$ kV, $\tau_{imp} = 30$ µs. A, C – rising slope, B, D – falling slope*

$I_{tot}$ is the total current measured by the current probe and $I_{displ}$ is the displacement current, i.e. the current proportional to the capacity $C_{el}$ of the electrode system without the discharge and to the steepness of the voltage impulse front $dU/dt$. To measure the displacement current the electrode arrangement was replaced by a unit capacitor of the same capacitance as the discharge gap. The main measured characteristic values (maximal discharge current $I_m$ and voltage $U_0$ of discharge ignition) of the discharge are given in fig. 2. The pictures show different structure of the discharge for rising and for falling slopes both for positive and for negative HV impulses. The channel structure of individual microdischarges is more pronounced for rising slope of positive HV while the discharge structure is practically the same for the impulse falling slope of both polarities and consists of short bright spots with very weak diffusive part connected to the spot. The visible length of microdischarges seen in the pictures done with speed camera is about 1.2 mm for rising impulse slopes of both polarities and $U_m = 8$ kV.

The discharge current in oscillograms is presented in most cases (i.e. for all parts of the HV impulse and both polarities) by a single impulse. Nevertheless there are rare cases when the current curve shows a small number of discrete impulses (not more than 4-5) although there are seen more than 30 channels in the picture of the corresponding discharge.

Analysis of packets of discharge currents (20 discharge events) for $U_m = 8$ kV and 30 µs pulse width shows that maximal values of the discharge current pulses at the rising part of positive voltage impulse can be 2-3 times higher than the same for the discharge at the falling impulse part. Contrary to it the discharge current maximal value for falling part of negative voltage impulse can be 1.5-2 times higher than for the rising voltage impulse front and have longer width (35 ns). According to [6] this difference can be explained by different pre-ionization concentration of charged species in the gap left after previous discharges.

*Fig. 3 – Discharge structure and oscillograms for sine voltage. $U_m = 3.92$ kV, $f = 15$ kHz.*

*Fig. 3* shows pictures of the discharge structure and oscillograms for sine voltage for the same electrode configuration and near discharge conditions. Contrary to an impulse case the discharge patterns as well as the current oscillograms show discrete microdischarge channels and current
impulses for both half-cycles. The comparison with the impulse voltage case indicates the following features of the sine discharge that are different from the impulse voltage case: a) weak and short microdischarge channels during positive half-cycle and small values of corresponding discharge currents; b) discrete character of microdischarge current pulses; c) extremely weak microdischarges during negative half-cycle.

All the above presented discharge characteristics correspond to one value of voltage impulse duration $\tau_{imp} = 30 \mu s$. The change of $\tau_{imp}$ value leads to a marked change of the discharge structure and current values. The integral pictures of the discharge for different $\tau_{imp}$ values were done using a photo camera (exposition 1/100 s) and are shown in Fig. 4 together with $I_{dis} = f(\tau_{imp})$ curves. As it is seen the character of $\tau_{imp}$ influence depends on the impulse polarity and the moment of the discharge appearance, i.e. the rising or falling slope of the voltage impulse.

| $\tau_{imp} = 0.5 \mu s$ | $\tau_{imp} = 45 \mu s$ |
|--------------------------|--------------------------|
| ![Graph](image1.png)     | ![Image2.png]            |

Fig. 4 – Discharge current amplitudes (A) and photos of the discharge (B) for different $\tau_{imp}$ values of impulse voltage, $U_m = -8$ kV. Photos are done in 1 min after discharge ignition. Exposure time 1/100 s.

It has been shown in [6] on base of experimental investigation of traditional barrier discharge driven by periodic impulse voltage of different impulse duration $\tau_{imp}$ that a change of $\tau_{imp}$ value leads to different discharge formation. An increase of $\tau_{imp}$ from 0.2 to 10 $\mu$s gives a reduce of the discharge current for rising voltage slope and a change of the current form and an increase of its amplitude at the falling slope of the voltage curve. This result is explained in [6] by a comparability of drift time of charged particles and the impulse duration which leads to a formation of volume charge in the gap. This charge changes the electric field distribution in the gap and the conditions of the subsequent discharge appearance. It is assumed in the present work that the above proposition can be fully applied to SDBDs where the volume charge in the pre-ionization stage is supported by the surface charge on the barrier surface. In this case it is possible to explain the difference in the surface discharge structure and current values with the $\tau_{imp}$ increase. Besides, it must be noted that the increase of $\tau_{imp}$ for a constant value of voltage frequency leads to a decrease of the pause between subsequent voltage pulses, i.e. the time between the discharge at the impulse falling slope and the subsequent discharge at the rising slope of the following voltage impulse.

| A | B | C | D |
|---|---|---|---|
| ![Image3.png] | ![Image4.png] | ![Image5.png] | ![Image6.png] |

Fig.5 – Photos of discharge structure at different moments after the discharge ignition: 1 s (A), 10 s (B), 20 s (C) and 30 s (D) for $U_m = +5$ kV and $\tau_{imp} = 5 \mu s$. 
An additional feature of the surface discharge has appeared when photos of the discharge were done at different moments after the discharge ignition (Fig. 5). It is seen that the discharge structure changes with time of discharge existence. As there was no special cooling of the electrode this change may be attributed to some heating of the gas after several seconds. The result means that the discharge characteristics may be quite different when a single impulse or periodic impulse voltage are applied.

A three electrode arrangement was used in the present work to measure the current extracted from the surface discharge plasma layer by a dc potential of the third electrode. It was found out that the voltage impulse duration has an additional influence on the value of the extracted current $I_d$. The measured extracted current is shown in fig. 6 A for different negative impulse voltage values $U_{imp}$. Fig. 6 B is for different extracting dc voltage $U_d$, in this case impulse voltage $U_{imp}$ is +8 kV, frequency $f$ = 15 kHz. These results are a direct consequence of the $\tau_{imp}$ influence on the SDBD plasma formation. The $I_d$ strong dependence on $U_d$ for a three-electrode arrangement has been shown in [7]. The character of $\tau_{imp}$ influence on $I_d$ varies with different $U_d$ polarity as it is seen in Fig.6 B. With positive $U_d$ polarity the quantity of negative species (negative ions and electrons) that constitute the extracted current just slightly increase for $\tau_{imp}$>20 $\mu$s while the extracted current of positive ions becomes 1.8 times higher with an increase of $\tau_{imp}$ from 0.5 $\mu$s up to 10 $\mu$s with negative d.c. voltage. Further increase of $\tau_{imp}$ does not change $I_d$ which means that the main quantity of positive ions is produced during first 10 $\mu$s of voltage application.

![Fig. 6 – Influence of positive d.c. potential of third electrode and voltage impulse duration $\tau_{imp}$ on extracted current $I_d$. In Fig. 6A curve B is for -5.5 kV, C -6 kV, D -7 kV and $\tau_{imp}$ = 5 $\mu$s](image)

4. Conclusions

The SDBDs driven by periodic impulse high voltage have peculiarities that differ this type of discharge from the sine voltage case:

- the channel structure of the impulse surface discharge is more pronounced especially at the rising slope of the voltage impulse of both polarities;
- the discharge current in the oscillograms is presented by a single pulse for all voltage impulses with slope steepness of $\geq$ 50 V/ns used in the present work;
- an increase of the voltage impulse duration from 0.5 ns to 50 ns can change the discharge structure as well as the discharge characteristics. This effect can be attributed to a change in the pre-ionization phase of the discharge.

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