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Volume-surface barrier discharge in dried air in three-electrode system fed by impulse high voltage with nanosecond rise time*

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Abstract. Results of experimental investigation of a volume-surface barrier discharge in a three-electrode system under periodic impulse voltage applied to the surface discharge (SD) electrodes and a d.c. potential applied to an additional third electrode are presented. It is shown that there is a strong influence of polarity and amplitude of the d.c. potential on the direct current "extracted" out of the surface discharge plasma layer by electric field of the third electrode. The amount of charged positive species that constitute the "extracted" current prevails under positive impulse voltage for low values of the negative d.c. potential of the third electrode. The amount of negative species prevails with higher values of the positive d.c. positive of the third electrode.

1 Introduction

Present paper is aimed at investigation of a volume-surface dielectric barrier discharge in an electrode system that includes a typical two-electrode arrangement used to form surface barrier discharge [1] and a third plane d.c. voltage electrode placed at a distance from the plasma layer of the surface discharge. It has been shown previously [2] that a flow of charged species to the third electrode can be formed in the gas gap above the surface discharge plasma layer in such electrode system.

Surface dielectric barrier discharge in a two-electrode system has been extensively investigated during last years because it can be used in different plasma technologies, such as gas and surface treatment [3], plasma-assisted ignition/combustion (e.g., [4,5]), intensive UV-light generation and so on. Main electric parameters of surface discharge, densities of active species produced during discharge existence, electric field values have been measured and calculated [6,7]. It has been shown in reference [8] that there is a certain similarity of processes in the discharge plasma of classical barrier discharge and of surface barrier discharge. More recent publications on experimental investigation and modeling of the surface barrier discharge give new material for understanding of the detailed mechanism of the discharge especially on its initial stages [1,9].

Results of experimental investigation of surface dielectric barrier discharge presented in different publications mostly describe measurements fulfilled under high a.c. applied voltage. Nevertheless there is evidence that in technological devices based on barrier or surface barrier discharge there appear certain advantages if an impulse high voltage is used to form the discharge. A possible application of nanosecond impulse surface discharge for different plasma-assisted technologies and measurements was discussed in a range of publications [7,10]. It was demonstrated that a plasma layer of surface discharge can be produced under pulsed nanosecond voltage at elevated pressures including the atmospheric pressure. Recent publications on investigation of barrier and surface barrier discharges under impulse high voltages of nanosecond and sub-microsecond duration demonstrate evident dependence of discharge characteristics on the parameters of the high voltage impulse form and duration [11,12]. Primary results found in reference [12] with unipolar symmetrical pulses show that the discharge behaves similarly to sinusoidal operated discharges whereas there is different behavior of unipolar-pulsed-driven barrier discharges. A comparison of sinusoidal and pulsed operated dielectric barrier discharges in an O_2/N_2 mixtures [13] demonstrates the influence of the duty cycle of pulsed operation while bipolar-pulsed-operated barrier discharges give

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similar results to unipolar-driven discharges. These results are for single microdischarges. A number of papers compare pulsed and sinusoidal operation involving large numbers of microdischarges in the discharge space. Such investigations have practical significance for technological application [7,14].

There are scarce recent publications known to authors that demonstrate an advantage to use volume-surface discharge as a source of charged species. Our previous experiments with a.c. surface barrier discharge [2] have shown that it is possible to get high values of charged species density in the gas volume above the surface discharge plasma layer when a third electrode with a d.c. potential is present in the gas gap and a "volume-surface discharge" is formed. The volume charge in the gas gap above the surface discharge plasma layer may even lead in this case to an appearance of single microdischarge filaments seen in the gap on the background of weak luminosity of the gas in the gap over plasma layer [15].

Investigations of a traditional dielectric barrier discharge in air carried out with a rectangular impulse high voltage applied to the electrode arrangement with dielectric barriers [16] give evidence of a significant influence of the voltage impulse amplitude and series resistor value on the discharge form (diffusive or filamentary) and on the time delay of the discharge appearance. The cited work has been done with a relatively low frequencies of the periodic signal (tens of Hz) and series resistor values in the range from 80 Ω (a diffusive form of the discharge) to 13×10^3 Ω (a filamentary discharge form). More recent work [17] using the same impulse generator has shown that it is possible to change the barrier discharge characteristics and even the discharge mode if such factors as the impulse repetitive rate, material of the barrier (ceramic or acrylic glass) and the series resistor value are varied.

There is a range of recent publications (theoretical and experimental) dedicated to physical mechanism of surface discharge development and processes that lead to the appearance and propagation of streamer channels of surface microdischarges [1,6,18]. Most of the investigations are fulfilled with sinusoidal voltage. The work by Grosch et al. [6] that deal with spatio-temporal development of a single channel of the surface microdischarge under sinusoidal voltage of 60 kHz frequency shows that there are at least two stages of the surface discharge development.

A short review of recent publications shows that the electric characteristics of surface discharge such as the discharge current, active power of the discharge, emission spectrum, discharge structure depend on a range of factors: electrode arrangement which governs the electric field distribution near the stressed electrode, barrier material, surrounding gas and its pressure, the kind and amplitude of high voltage applied to the stressed electrode: a sinusoidal or an impulse one and its frequency, single pulses or a periodic one and the polarity of the stressed electrode.

The aim of the experiments described in the present paper was to study such characteristics of the discharge that are important for technologies based on the surface discharge. These characteristics are the intensity of charged species formation in the discharge and the active power to produce charged species. The possibility to get an effective charge species formation in the discharge under periodic impulse high voltage of different impulse amplitude and duration and different repetitive rate was analyzed. The experiments were fulfilled with a volume-surface barrier discharge in air in a three electrode arrangement using an impulse periodic voltage applied to the main electrodes that produce the surface discharge, and a d.c. high potential applied to a third plane electrode placed above the plasma layer of the surface discharge. The main attention was paid to Volt-Ampere characteristics of the volume-surface discharge that in a three electrode system show the dependence of the current "extracted" from the plasma layer I_{D} on the d.c. potential value U_{DC} of the third electrode.

It must be noted that the possibility to use periodic impulse voltage to form the discharge in different technologies is based on the development of the solid-state converting equipment, including the development of solid material switchboards for high voltage sources. These sources can produce short (of nanosecond and microsecond duration) voltage pulses with frequencies up to tens of kHz and high voltage amplitudes up to 12 kV [16,17]. Such generator has been used in the present work.

2 Experimental

The electrode arrangement used in the present work was the same as one used in references [12–14] and included two electrodes to form the surface discharge and a third plane electrode to "extract" the direct current (Fig. 1). The surface discharge electrodes (1) and (2) were placed on both sides of a dielectric barrier of Alumina plate 1 mm of thickness. The surface discharge electrode (corona electrode) consisted of 10 strips of Ni 1 mm wide and 6 cm long connected between themselves. The space between the strips was 4 mm. The electrode on the reverse side of the plate (1) was a plane one made of Ni while the third plane electrode (3) placed 1 cm above the dielectric barrier was a steel plate 80×60 mm. The corona electrode thickness was about 30 μm. The electrode system was enclosed in a cell through which dried unfiltered air was drawn by means of a small compressor; the humidity of the air was estimated to be not more than 12% while the velocity of air at the electrodes was not more than 0.08 ms^{-1}. The sketch of the cell is given in Figure 1a. It shows the electrodes that constitute the upper and the bottom walls of the cell, while the side walls are of Plexiglas and permit to see the discharge. These side walls are at a distance more than 1 cm away from the edge of the electrode with the surface discharge and their height is about 1.5 cm.

The duration of high voltage impulse formed by the impulse generator was varied from 500 ns to 5 μs. Impulse front rise time was 150 ns and the falling part duration was 180 ns.

The frequency of pulses appearance was throughout 14 or 16 kHz, so the time between sequent impulses was about 65–70 μs. The results of earlier experiments [15] with a barrier discharge under short impulses (300–5000 ns) have

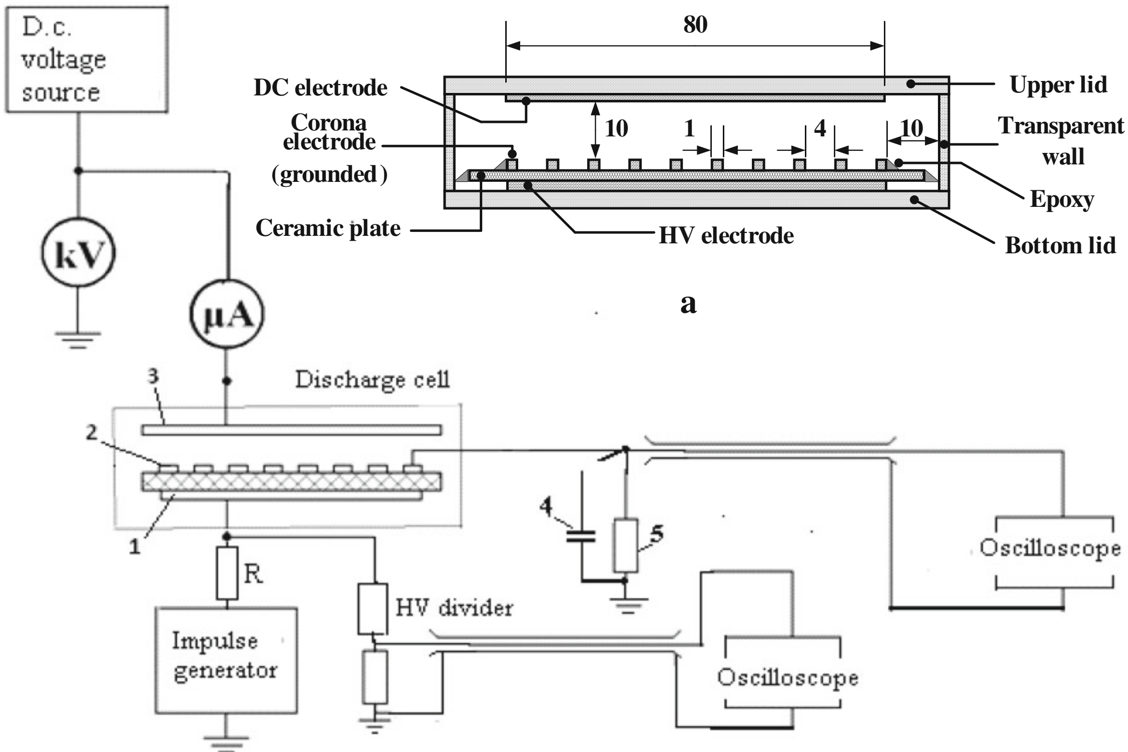

Fig. 1. Electric circuit with discharge cell (a): 1–3 – electrodes, 4 – measuring capacitor C_m; 5 – measuring resistor R_m; R – series resistor of impulse generator. All dimensions are in mm.

shown that the value of the series resistor R in the generator circuit (Fig. 1) can influence the form of the discharge. An analysis of the behavior of the impulse generator used to form a barrier discharge [16] has shown that there was no influence of generator parameters on the discharge characteristics for electrode systems with capacitance about 130×10^{-12} F and series resistor $R > 124\ \Omega$. The series resistor R in the present investigations was 500 Ω and the electrode capacitance for a multistripped corona electrode and ceramic barrier was not less than 135×10^{-12} F. So the parameters of the generator itself did not influence the surface discharge in our case.

The high voltage impulses were in all cases applied to the plane electrode (1), so the more stressed multistripped electrode (2) was "positive" relative the ground with negative impulses and it was "negative" with positive impulses from the generator. Hereafter the polarity mentioned attributes to the potential of the corona multistripped electrode.

Surface discharge was detected by measuring its current through a low inductance current sensors with $R_m = 2.4\ \Omega$ or $R_m = 7.4\ \Omega$ or by measuring the charge injected into the gap using capacitor $C_m = 44 \times 10^{-9}$ F. A TDS 2012 oscilloscope was used to register the signals. Some measurements of the discharge current were done with an oscilloscope DPO 7354 which has the frequency band width 3.5 GHz. The high voltage was measured by means of a capacitor divider Tektronix P6015 1000. The whole electric circuit is given in Figure 1 with a detailed sketch of the discharge cell.

3 Results and discussion

3.1 Surface discharge current

Surface discharge (SD) under impulse voltage of sufficient amplitude appears during the rising part of the voltage impulse (main discharge) and at the falling part of the voltage impulse (back discharge). This fact is well known and is described in many works as it is given in the introduction to the present paper. The choice of our experimental conditions was aimed to measure mainly the external characteristics of the discharge in a three-electrode arrangement: the current "extracted" from the plasma layer of the surface discharge, the active power of the surface discharge in a complex electric field formed by the applied impulse voltage and the additional electric field of the third electrode. A comparison of these characteristics to the characteristics for a.c. voltage was fulfilled.

Typical current and voltage impulse oscillograms are shown in Figures 2a–2c for different polarity of the impulse potential applied to the plane electrode (1). The current impulses in Figure 2 correspond to the rising part of positive impulse (B) and falling part of positive impulse (C).

The voltage impulse duration was 5 μs. The current curves $I(t)$ include a displacement current component $I_c(t) = f(C_m, dU/dt)$ and the surface discharge current component measured through the current sensor $R_{sh} = 2.4\ \Omega$. It must be noted that the discharge current in the oscillograms is presented by an envelope curve while

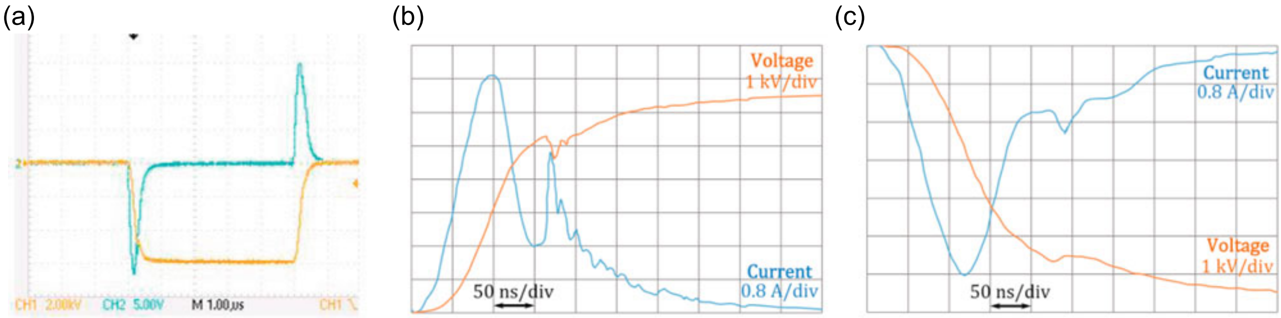

Fig. 2. Typical oscillograms of the voltage and current of surface discharge.

the pulses of individual microdischarges are not distinguished which is contrary to the case of the surface discharge current under a.c. high voltage. Such a result can be connected with short duration of the impulse discharge (approximately about 20–200 ns). The discharge is seen to exist only during the crest of the voltage impulse curve. It means that all microdischarges formed at different places at the edges of the strip electrodes appear practically at the same time. Values of dU/dt at the front and the falling part of the voltage impulse are equal to about 60 V/ns and minimize the time delay of individual microdischarge appearance.

Examples of current impulse oscillograms without the displacement current for the discharge at the front and at the falling part of the voltage impulse are given in Figure 3.

Oscillograms for a range of voltage impulse amplitudes show that the surface discharge under positive impulse potential is more powerful compared to the negative impulse case. The same is known for the surface discharge under positive and negative half-cycles of an a.c. high voltage. A certain statistical dispersion of the amplitudes and of the forms of the discharge current envelope curves was registered especially under positive high voltage impulses. An analysis of the discharge current oscillograms has shown that there was no clear difference between current forms and current amplitudes of the discharges with and without a d.c. potential of the third electrode. It was found as well that there is no difference in the discharge current if high voltage impulses of different duration (from 500 ns to 5 μs) were used. Main factor to influence the discharge current was found to be the amplitude of the impulse voltage. The current impulse duration tends to be longer with higher voltage impulse amplitudes especially under positive voltage and reaches 200 ns. The current impulse for the back discharge at the falling part of the voltage impulse with the same U_m value has shorter duration.

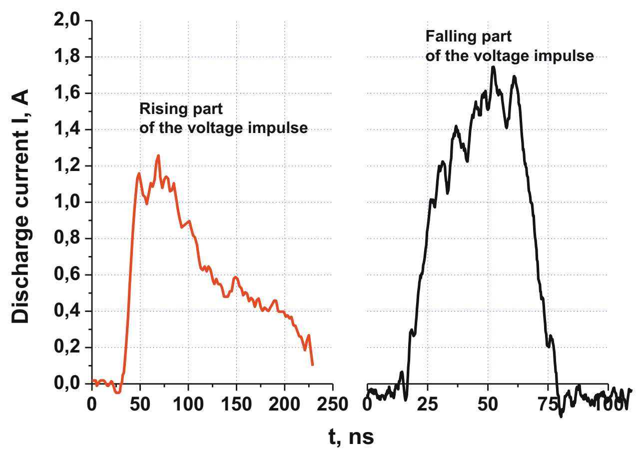

Fig. 3. Examples of current impulses of surface discharge at the rising and falling parts of the applied voltage impulse.

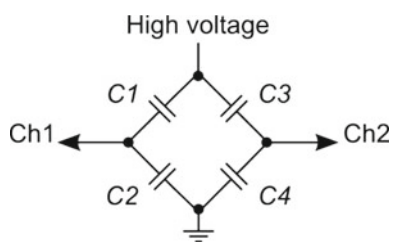

Fig. 4. Electric circuit to measure the Volt-Coulomb characteristic.

3.2 Volt-Coulomb characteristics

There are at least two methods to measure active power of gas discharge [19]. One of them is the calculation of the power using voltage and current time dependence curves [20]. The other is a well known method of Volt-Coulomb characteristics (Lissajous figures) used in many works to measure the active power of the discharge under sinusoidal voltage [21,22]. This method was used in present work to evaluate the active power of the impulse surface discharge. A sketch of the electric circuit to measure the power used in the present work is given in Figure 4.

The capacitors $C1$ and $C2$ form the high voltage divider. The element $C3 = 130 \times 10^{-12}$ F is the capacity of the surface discharge electrode arrangement and $C_m = C4 = 44 \times 10^{-9}$ F is the measuring element on base of three capacitors $C = 15 \times 10^{-9}$ F in parallel.

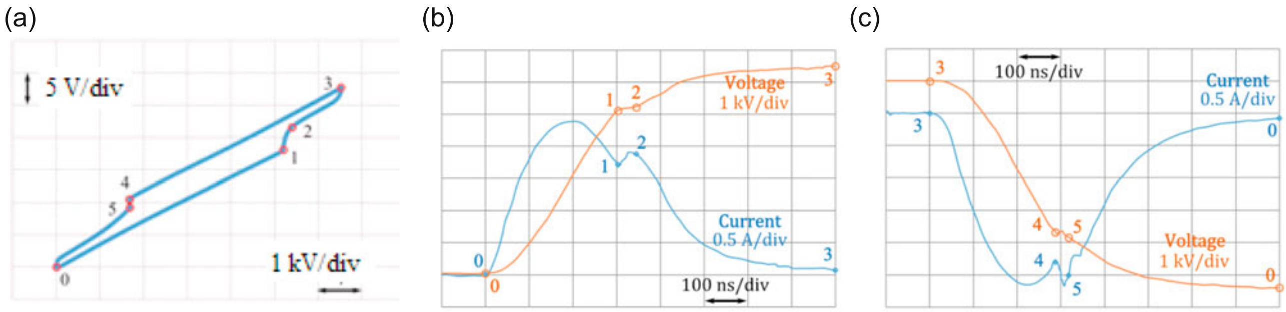

Fig. 5. Correlation between the Volt-Coulomb characteristic of impulse surface discharge and voltage and impulse current curves. (a) $U-Q$ curve; (b) current and voltage curves at the front of the voltage impulse; (c) current and voltage curves at the falling part of the voltage impulse.

Figure 5a shows a typical Volt-Coulomb ($U-Q$) characteristic of a positive impulse surface discharge from a multistripped electrode. A negative impulse high potential is applied to the plane electrode (1). The multistripped electrode (2) is grounded through the capacitor $C_{\rm m}$. Figure 5a can be compared to the current and voltage curves shown in Figures 5b and 5C. Figure 5b is for the rising part of the voltage impulse curve and Figure 5c is for its falling part.

The part 0-1 of the $U-Q$ curve corresponds to the front of the impulse voltage curve and shows proportionality of the charge on the electrodes to the applied voltage without a discharge. Only capacity current is seen in the oscillogramm. From point 1 to point 2 there is seen a smooth transition of the $U-Q$ curve from the discharge absence (point 1) to the discharge regime (point 2). The discharge lasts a short time and the part of the curve till point 3 corresponds to a very small increase of the voltage without the discharge (practically flat part of the impulse curve in Fig. 5b). Additional charging of the electrodes capacity corresponds to part 2-3 of the $U-Q$ characteristic. The falling part of the voltage impulse shown in Figure 5c begins at point 3. Part 3–4 corresponds to a decrease of the charge of the electrodes capacity and only a capacity current is seen in the oscillogramm. This process lasts until point 4 where the back discharge created by charges deposited on the dielectric barrier begins. Back discharge stops at point 5 after which there is a smooth transition to the end of the voltage pulse (point 0).

The oscillograms of Volt-Coulomb characteristics permit to calculate the active power P of the discharge which for a periodic voltage can be found using the area S of the $U-Q$ loop. This procedure is well known for the discharge under sinusoidal voltage (e.g., [19]). In our case of an impulse periodic voltage:

$$P = f \times \oint U_{\rm appl}(t){\rm d}Q = f \times C_{\rm m} \times \oint U_{\rm appl}(t){\rm d}U_{\rm meas} = f \times C_{\rm m} \times S, \quad (1)$$

where $U_{\rm appl}(t)$ is the applied impulse voltage with the repetitive frequency f:

$$S = \oint U_{\rm appl}(t){\rm d}U_{\rm meas}. \quad (2)$$

Dimensions of S in equation (2) are in V^2. The dimensions on the Y axis in Figure 5a are in V/div. and correspond to the measured values of the voltage $U_{\rm meas}$ on the measuring capacity $C_{\rm m}$. The measured values of applied voltage on X axis are in kV/div. The charge Q is defined as $Q = U_{\rm meas} \times C_{\rm m}$ and is equal to the charge created by the discharge processes.

The applied voltage amplitude $U_{\rm m}$ in the $U-Q$ loop is represented by the projection of the segment 0–3 on the applied voltage axis (Fig. 5a).

Values of active power calculated using $U-Q$ loops for different voltage impulse amplitudes are shown in Figure 6 as a function of positive d.c. voltage ($+U_{\rm DC}$) applied to the third electrode. The same repetitive rate of periodic impulse voltage $f = 16.1$ kHz and $\tau_{\rm imp} = 5$ μs was used. The amplitude of the impulse voltage pulses was found to be the main factor to define the active power of the surface discharge. The influence of $U_{\rm DC}$ values on the active power values was found to be weak the dispersion of the values does not overcome 10–15% which is in the range of experimental accuracy. Only a weak increase (about 10%) of the power for higher values of the impulse voltage amplitudes is seen if the d.c. potential is higher than 5–7 kV. Weak dependence of active power of the impulse surface discharge on the d.c. potential of the third electrode can be explained by short time of the discharge existence (20–200 ns) compared to the applied voltage impulse duration $\tau_{\rm imp} = 5$ μs.

Figure 7 shows a comparison of active power values measured for different $U_{\rm m}$ of impulse voltage and equal peak-to-peak (p/p) values of a.c. voltage of the same frequency 16.1 kHz. There was no d.c. voltage during the above measurements. The results permit to see that the surface discharge under impulse voltage has less power consumption than under a.c. voltage of the same amplitude and frequency.

3.3 "Extracted" current

The current $I_{\rm d}$ in the d.c. voltage circuit was registered only with an appearance of surface discharge and when a certain potential was applied to the third electrode. No direct current was measured if there was no surface

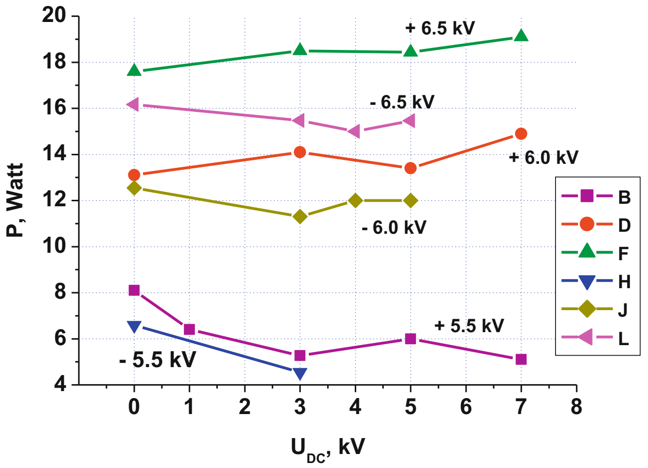

Fig. 6. Dependence of active power P of impulse surface discharge on the positive d.c. potential U_{DC} of the third electrode. Amplitude values (U_{m}) and polarity of the voltage impulse are given in the figure.

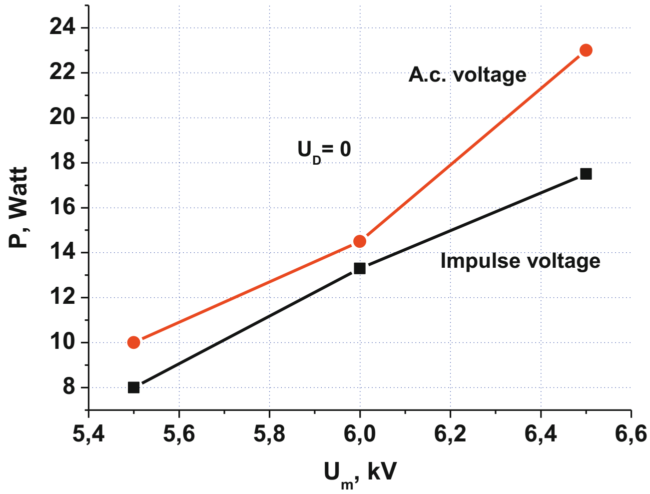

Fig. 7. Active power of the surface discharge under impulse and a.c. voltage for $U_{\mathrm{D}} = 0$. Values of U_{m} correspond to impulse voltage amplitude and to p/p values of the a.c. voltage.

discharge even for sufficiently high values of the potential on the third electrode. Such result has been registered for impulse and for a.c. voltage that form the surface discharge. The dependence of the I_{d} values on the potential of the third electrode $I_{\mathrm{D}} = f(U_{\mathrm{D}})$ for different values of the positive impulse voltage amplitudes are shown in Figures 8a–8d together with currents "extracted" from plasma layer of surface discharge under a.c. voltage. The values of U_{m} in Figure 8 correspond to amplitude values of impulse voltage and to peak-to-peak values of the a.c. voltage.

Earlier experiments with a.c. voltage and the same electrode arrangement [2] have shown that the main factors to influence the "extracted" current to the third electrode were the applied voltage amplitude and especially the value and the polarity of the d.c. potential of the third electrode. Experiments with surface discharge under a.c. voltage fulfilled in the present work gave the same result. The values of I_{D} for impulse high voltage were found to be lower than for a.c. voltage for the same conditions and to depend mostly on the amplitude and the polarity of the d.c. potential on the third electrode. The amplitude of the impulse voltage applied to corona electrode had much less influence on the "extracted" current (Fig. 9).

Such difference to an a.c. case we suppose to be connected with different time τ_{d} of the surface discharge existence during one half-cycle of the a.c. voltage or during voltage impulse. The time τ_{d} measured on the oscillogram for a.c. voltage and frequency 14 kHz [23] was found to be about 25–30 μs. So the flow of charged species to the third electrode with an a.c. applied voltage exists during a relatively long time. The time between sequential discharge bursts at the positive and negative half-cycles is also about 25 μs. The oscillograms of the impulse surface discharge currents (an example of the current impulses in Fig. 3) show that the time of all streamers development was only about 20–200 ns. As the front duration of the voltage impulse does not change much with its amplitude there is just a weak influence of impulse voltage amplitude on the "extracted" current compared with the influence of the d.c. potential of the third electrode (Fig. 9). Contrary to the a.c. case the pause between the discharge bursts of sequential pulses of impulse voltage is 62–70 μs for frequency 14–16 kHz.

To explain the behaviour of charged species flow in the gas gap the time of species movement from the plasma layer to the third electrode must be evaluated. The distance to the third electrode was $d = 1$ cm, the mean value of electric field in the gas gap above the plasma layer for maximal value of $U_{\mathrm{DC}} = 10$ kV is $E/d = 10$ kV/cm. In normal gas conditions it gives $E/N = 40$ Td. Main species that live in gas phase of streamer in air DBD during about 100 μs with density more than 10^{10} cm^{-3} are according to reference [24] O^+, O_2^+, N_4^+, O^-, O_2^-. Mean values of the drift velocity for these species in the field 40 Td are $v_{\mathrm{d}} = 1$ cm/s for positive species and $v_{\mathrm{d}} = 2.5$ cm/s for negative ones [25]. So the time to cross the gas gap for these ions in average field 10 kV/cm is about 50–100 μs for positive ions and about 25 μs for negative ions. It means that charged species formed in one half-period of an a.c. applied field would be still in the gas gap when a new portion of species in the next half-period appears. The dark period without a discharge is less than the time of charged species to drift to the third electrode, and a volume charge could be accumulated in the gas gap. This charge can govern the behaviour of charged species in the gas gap during the discharge under a.c. voltage.

This is not the case for the discharge under impulse voltage. The time between discharge bursts at the rising and at the falling parts (back discharge) of a single voltage impulse of 5 μs duration is just about 5 μs. The time between sequential voltage impulses is about 65 μs for $f = 16$ kHz. So the charged species that appear during one impulse and move to the third electrode with $U_{\mathrm{DC}} = 10$ kV have time enough to leave the gas gap before the discharge burst of sequential impulse occurs.

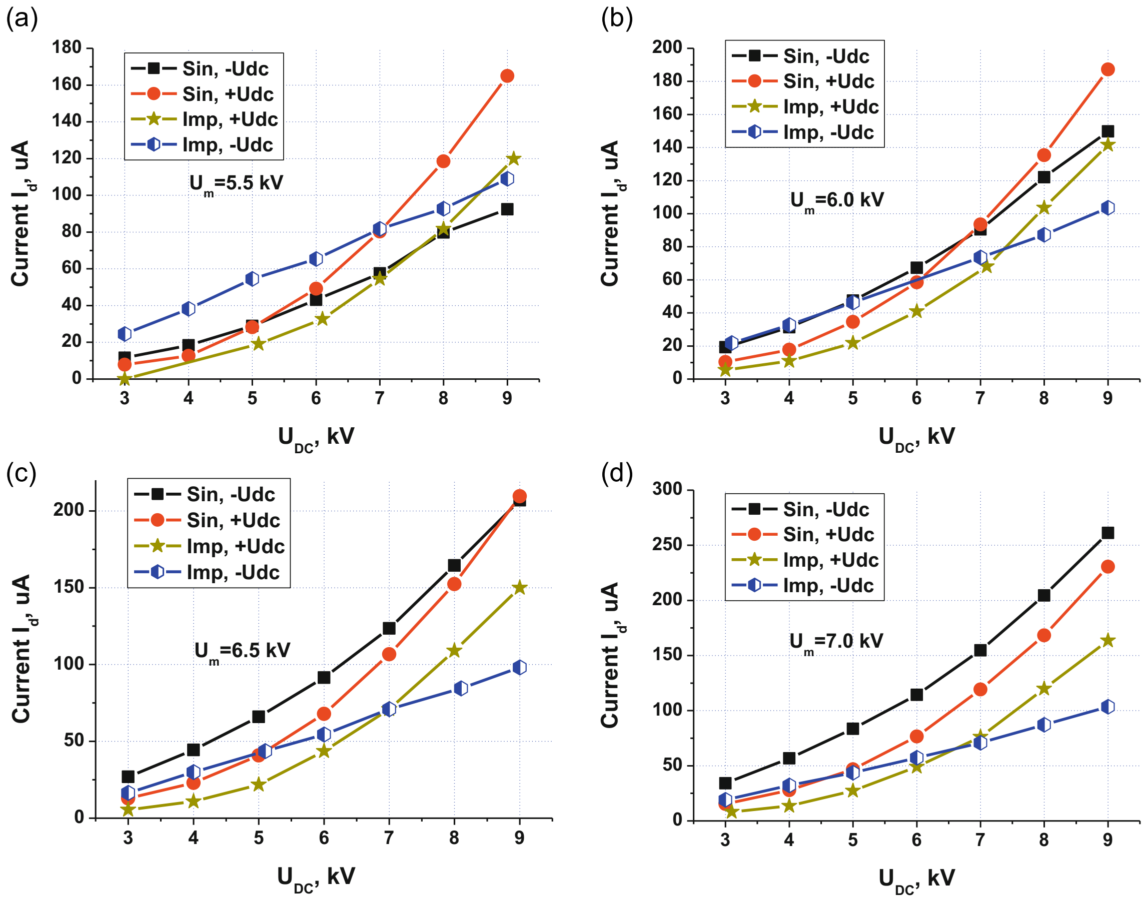

Fig. 8. Comparison of "extracted" currents as a function of $U_{\rm DC}$ for different positive impulse voltage amplitudes and different values of a.c. voltage (peak-to-peak values).

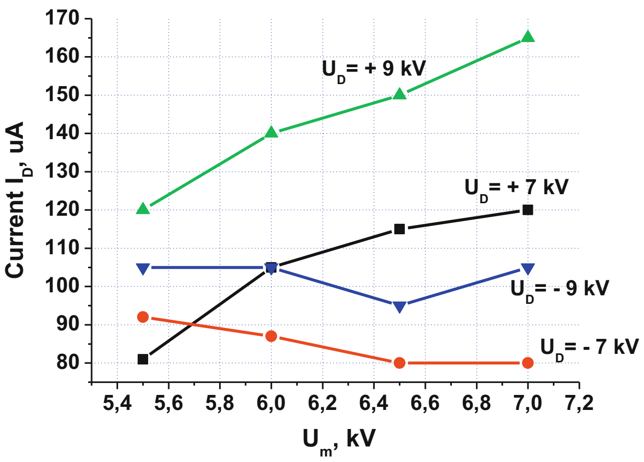

Fig. 9. Comparison of "extracted" currents as a function of positive impulse voltage amplitudes for different values and polarity of the $U_{\rm DC}$.

The "extracted" current with positive third electrode consists of negative species (negative ions and electrons) while positive ions are repulsed. With positive polarity of the corona electrode and positive third electrode positive ions can drift away only outside the streamer channel through its side borders [26]. Negative species in this case tend to move mostly towards the positive corona electrode with high potential than to the third electrode if its potential is not too high. The "extracted" current consisting of positive ions for the case when $U_{\rm DC}$ is negative and voltage impulses are positive can exceed the current consisting of negative species for $+U_{\rm DC}$ and the curves in Figure 8 confirm such supposition. With higher values of $U_{\rm DC}$ the curves $I_{\rm D} = f(U_{\rm DC})$ for positive and negative d.c. potential cross each other. The crossing point depends on $U_{\rm m}$ and moves to lower $U_{\rm DC}$ values with higher voltage impulse amplitude (Tab. 1).

Table 1. The $U_{\rm DC}$ values for which the 'extracted' current with $+U_{\rm DC}$ is equal to one for $-U_{\rm DC}$ in Figure 8.

$U_{\rm m}$, kV	5.5	6.0	6.5	7.0
$U_{\rm DC}$, kV for crossing point (impulse voltage)	7.5	7.3	7.0	6.7
$U_{\rm DC}$, kV for crossing point (a.c. voltage)	5.0	6.7	9.0	>10

The same crossing of the $I_{\rm D} = f(U_{\rm DC})$ curves is seen for the discharge under a.c. voltage.

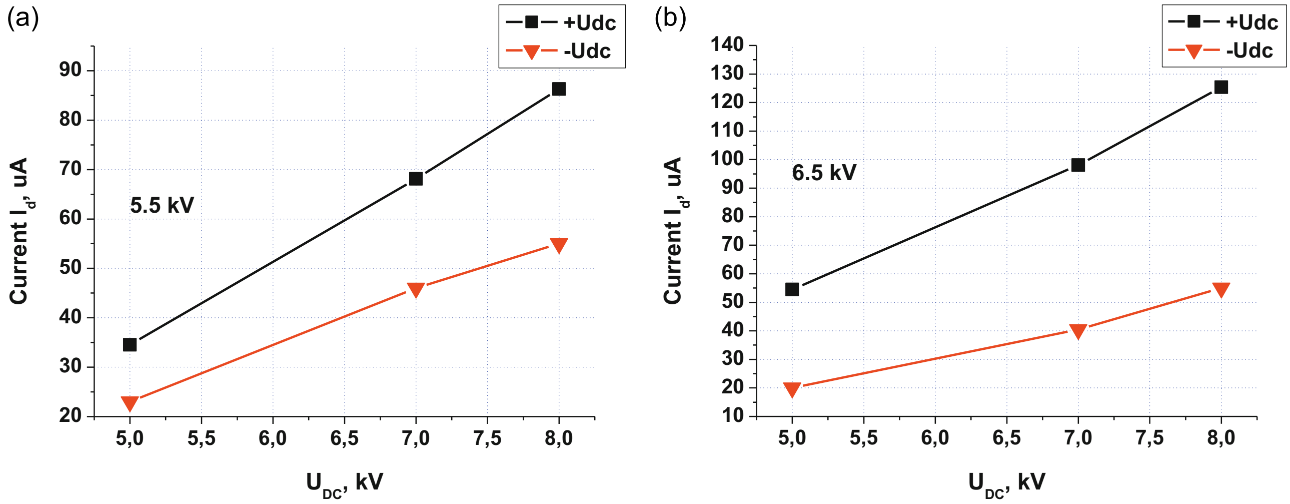

Fig. 10. Comparison of "extracted" currents for $U_\mathrm{m} = 5.5$ kV (a) and $U_\mathrm{m} = 6.5$ kV (b) and for different values and polarity of U_DC.

The experimental results presented in Figure 8 show that the above conclusion is right only for one single combination of conditions: positive impulse voltage on the corona electrode with impulse amplitudes not higher than +6.5 kV and negative $U_\mathrm{DC} < 8$ kV. With higher negative U_DC values the "extracted" current for positive corona exceeds the current for a negative one (Fig. 8). With negative corona (negative impulse on the corona electrode) the "extracted" current for all positive U_DC values is higher (Fig. 10) than for negative third electrode.

The relation between "extracted" current values shows that for positive U_DC when the charged species that constitute the "extracted" current are negative their amount (and consequently the current) depends on the polarity of the corona electrode. It means that the "extracted" current depends on the combination of the polarity of the impulse voltage on the corona electrode and the polarity of the U_DC potential of the third electrode.

The situation in the gas gap between the plasma layer and the third electrode is much more complicated in realty than it is proposed above and an additional analysis including additional experimental data on the surface discharge characteristics and calculations of electric fields in the gas gap are needed. Such calculations must take into account the electric field of the corona electrode, the field of the charges on the barrier surface, the potential of the third electrode and the electric field of the possible volume charge in the gas gap. First results of such calculations based on a simple approach to the problem were presented in reference [23]. More profound analysis of the problem will be the subject of our future work.

3.4 Influence of the impulse voltage duration and repetitive rate of voltage impulses on the intensity of charged species formation

Brief analysis of experimental results on the influence of different duration and repetitive rate of voltage impulses on the "extracted" current values has shown that only the repetitive rate can change the current whereas the impulse duration in the used range has no visible effect (Tab. 2). Such result can be explained once again by short time of the surface discharge existence τ_D during every single impulse. The discharge is formed at the front of the voltage impulse and ceases to exist at the moment when the impulse amplitude is reached. After that the discharge can not appear during all time τ_imp till the moment of the back discharge formation at the falling part of the impulse. The ratio $\tau_\mathrm{D}/\tau_\mathrm{imp}$ is small for all used values of impulse duration. With $\tau_\mathrm{D} = 50$–200 ns and $\tau_\mathrm{imp} = 500$ ns the ratio $\tau_\mathrm{D}/\tau_\mathrm{imp} = 0.1$–$0.4$ and decreases still more with an increase of the impulse duration. It can be supposed that for very short impulses with $\tau_\mathrm{imp} \leq \tau_\mathrm{discharge}$ the duration of voltage impulse would influence the discharge characteristics.

Table 2. The "extracted" current values I_D for different duration and repetitive rate of voltage impulses.

U_m, kV	U_DC, kV	I_D, μA	τ_imp, μs	f, kHz
6.5	8.6	100	5	14
6.5	8.7	105	1	14
6.5	8.6	98	0.5	14
6.5	8.6	43	0.5	5

3.5 Influence of the distance to the third electrode on the "extracted" current values

All main experimental results presented in the present paper were achieved with the same length d of the gas gap between the barrier surface and the surface of the third electrode. An increase of the gas gap width means a decrease of the electric field in the gap if the same values of the applied impulse voltage are used. Figure 11 demonstrates the comparison of the values of the measured "extracted" currents for two d values for the same

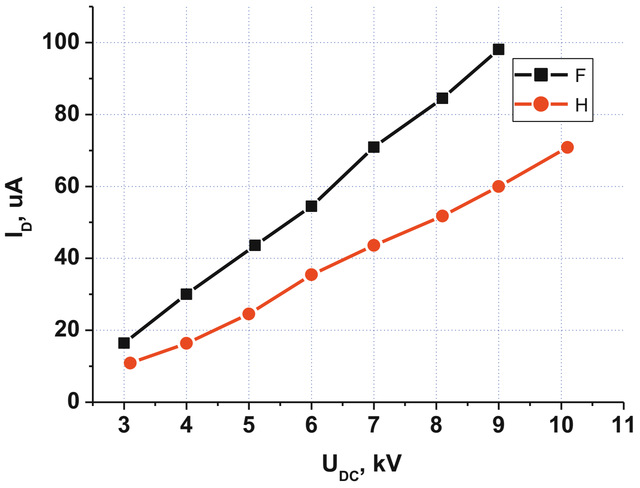

Fig. 11. Comparison of "extracted" currents for different distances from barrier surface to third electrode. $U_m = 6.5$ kV, curve F is for $d = 1$ cm, curve G is for 1.4 cm.

all other conditions: the same negative impulse voltage on the corona electrode $-U_m = 6.5$ kV, the same voltage impulse length 5 μs and $f = 16.1$ kHz. The difference of the current values I_D for the same U_m is evident, but the comparison of I_D for the same values of the applied electric field in the gap $E_m = U_m/d$ shows practically the same values of the "extracted" current. It means that the conditions to form the surface discharge at the edges of the corona electrode did not change with change of the distance d in the used range of lengths. So it can be concluded once again that the "extracted" current values are mainly influenced by the electric field at the corona electrode the evaluation of which needs an additional investigation.

4 Conclusions

(a) Experiments have been carried out to define the efficiency of charged species formation in volume-surface discharge under impulse high voltage with nanosecond rise time. The achieved results with impulse voltage were compared with experimental characteristics of discharge under a.c. voltage using identical three-electrode system and the same conditions of the surface discharge. The comparison has shown different behavior of the processes that go on in the used electrode system under high voltage of different form.

(b) The surface discharge under impulse voltage has been shown to exist only during short time (about 20–50 ns) at the rising part of the applied voltage impulse and at its falling part of the impulse (back discharge). The dark pause without a discharge under impulse voltage lasts about 65–70 μs for frequency 14–16 kHz. Long pause is sufficient for all charged species to drift to third electrode with d.c. potential. In case of a.c. voltage of the same frequency the dark pause lasts about 25 μs and a volume charge can be accumulated in the gas gap over the plasma layer. As a result the current I_D "extracted" out of impulse plasma layer of the discharge by d.c. voltage does not change much with voltage impulse amplitude. Only with high values of positive U_{DC} there can be an increase of I_D with an increase of the impulse amplitude. I_D is significantly increased by the d.c. potential of the third electrode for both U_{DC} polarities. It has been found additionally that the amount of the "extracted" current depends on the polarity of high voltage impulse which forms the surface discharge.

(c) The analysis of the experimental results permits to conclude that the amount of the charged species that constitute the "extracted" current depends on the combination of the amplitude and the polarity of the impulse voltage that form the surface discharge and the value and the polarity of the d.c. voltage of the third electrode. The "extracted" current increases essentially with positive impulse voltage amplitude when the electric field of the positive d.c. voltage in the gas gap exceeds 9–10 kV/cm.

(d) The duration of high voltage impulse in the range from 500 to 5000 ns does not change the "extracted" current values if the repetitive rate of voltage impulses is the same. The decrease of the impulse repetitive rate leads to practically proportional decrease of the "extracted" current for the same values of the d.c. voltage and the same impulse amplitude.

(e) The experiments have shown that active power of the surface discharge under a.c. voltage exceeds active power of the discharge under impulse voltage for the same all other conditions. The excess is about 35% in the absence of the d.c. voltage on the third electrode and increases with the impulse amplitude and d.c. field in the gas gap.

(f) It has been found that an elongation of the gas gap between the barrier surface and the third electrode does not change the "extracted" current values if the electric field in the gap does not change. It means that in the experimental conditions of the presented work the main component of the electric field which defines the delivery of charged species to the third electrode is the field at the corona electrode formed by the applied voltage.

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