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HIGH VOLTAGE PULSES CIRCUIT FOR GENERATING A PLASMA PLUME AT ATMOSPHERIC PRESSURE

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Abstract. Study of an atmospheric pressure plasma generator driven by a particular electrical circuit is presented. Electrical circuit consists of a high voltage pulses generator and a common dc high voltage source, parallel connected. The present work was focused to the enhancement of the high voltage pulses production. A method to optimize its operation has been devised.

1. INTRODUCTION

Cold plasmas generated at atmospheric pressure comprise a broad range of applications due to the possibility to process thermally sensitive materials (*e.g.* [1–7]). Plasma generator considered here is equipped with an electrical supply block consisting of two voltage sources parallel connected. One of them is a circuit that produces a train of negative high voltage pulses with peak value of about -4kV, whereas the other is a conventional dc voltage source whose output voltage can be varied in the range from -400 V to -1000 V. The purpose of this approach, whose principle has been previously described in [8], is to avoid the complexity of the classical solutions based on kilovolts dc sources, rf or microwave fields (*e.g.* [9–13]). The present work was focused to the improvement of the high voltage pulses source and its operation regime.

2. EXPERIMENTAL SETUP

The block diagram of the experimental setup is shown in Fig. 1. The two electrical voltage sources parallel connected are the high voltage pulses generator HVPG which ignites periodically the electrical discharge and the dc high voltage source HVDC which sustains the electrical discharge, respectively. Operating principle, is based on the well known peculiarity of an electrical discharge in gases, namely that, the voltage necessary to maintain it is lower than the voltage required to ignite it [14]. A diode network consisting of diodes D_1 and D_2 composes the two voltages. Resulting voltage is applied to the cathode K of the plasma source. An unit Spellman

SL150 was used as dc high voltage source. This equipment allows to vary output voltage in a wide range and has as built in available function, the limitation of the output current I_{dc} at a preset value. Supplementary, a ballast resistor R_b was inserted into dc electrical circuit, which was used both as current limiter and current sensor. High voltage pulse generator HVPG, comprising driver Dr, power MOSFET tran-

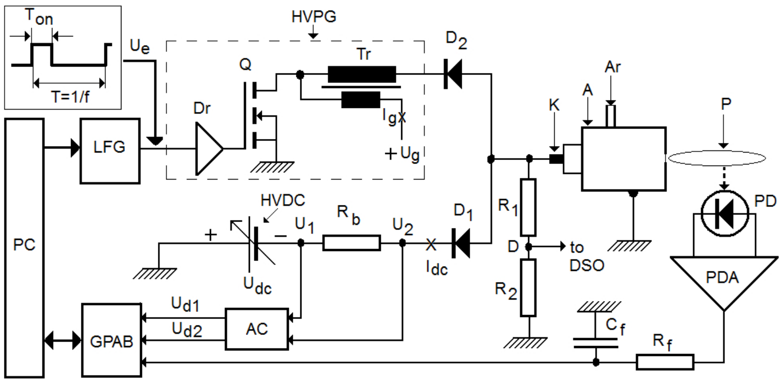

Fig. 1 – Block diagram of the experimental setup. A-anode; K-cathode; P-plasma plume; R_1/R_2 voltage divider; DSO-digital oscilloscope; D_1, D_2-high voltage rectifiers; R_b-ballast resistor, HVDC-negative high voltage source; LFG-low frequency signal generator; PD-photodiode; PDA-photodiode amplifier; R_f/C_f-low pass filter cell; AC-adapter circuit; GPAB-general purpose acquisition board; PC-personal computer. HVPG (dotted rectangle) is high voltage pulses generator consisting of driver Dr, power MOSFET transistor Q and high voltage pulse transformer Tr.

sistor Q and high voltage pulse transformer Tr (dotted rectangle in Fig.1), operates as a flyback converter. In this way, high voltage pulses can be obtained for a relative low transformation ratio [15, 16], this feature representing the main advantage of the flyback topology considered for this application. The transistor Q (IRF 840 [17]) is driven by the square wave excitation voltage U_e, with frequency f and pulse length T_{on}, provided by the low frequency signal generator (LFG). The frequency f can be varied in the range from 0.1Hz to 100Hz whereas pulse length T_{on} has been kept constant at 1ms. As a result of current switching through step-up transformer Tr primary coil, performed periodically by transistor Q, a train of high voltage pulses occurs across its secondary coil. A voltage divider composed of resistors R_1 and R_2 (voltage ratio $\simeq 0.15 \times 10^{-3}$) allows to display by means of a digital oscilloscope connected to point D, the waveform of the voltage applied to cathode K. In Fig. 2 is shown the waveform of a high voltage pulse (bottom trace) and its correlation with excitation voltage U_e (top trace). Each sudden current interruption through primary coil of the transformer Tr, triggered by falling edge of the excitation voltage, generates a negative high voltage pulse. The circuit is supplied by a dc source delivering the voltage U_g which can be varied in a range from 0V to 5V. Theoretically, the pulses voltage peak value increases with increasing of the parameters U_g or T_{on}. Due to the limitations related to the transformer Tr core magnetic properties, the pulses voltage peak was modified only by varying the voltage U_g, pulse length T_{on} remaining fixed. Diode D_2 rectifies the high voltage pulses occurring at the secondary coil terminals of transformer Tr blocking the positive polarity of the pulses. Diode D_1 blocks the high voltages pulses to be applied to the dc high voltage output.

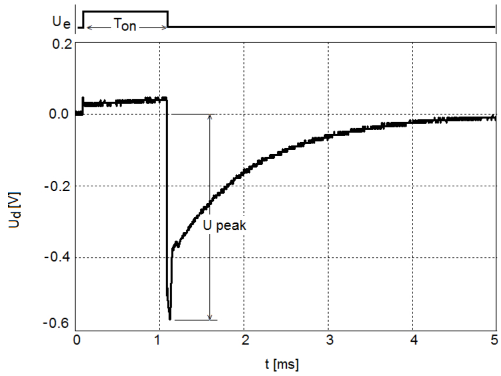

Fig. 2 – Top trace: Waveform of the excitation voltage U_e. Bottom trace: Waveform of a high voltage pulse recorded by a digital oscilloscope connected to point D. $U_{peak} \approx -0.57$V corresponds to output pulse voltage peak value ≈ -3.88kV. Experimental conditions: U_{dc}=0 (no plasma) U_g=2V, f=100Hz, T_{on}=1ms.

In order to test HVPG operation a plasma source consisting of a cylindrical tube made of brass, electrical connected to ground (with role of anode), has been used (Fig. 3). The cathode K is a iron wire passing along the longitudinal axis of the cylindrical tube. The main characteristic dimensions of the plasma source are: cathode diameter $d = 2$ mm, brass tube inner diameter $D = 7$ mm, output hole diameter $a = 2$ mm. As a carrier gas was used Ar. The gas flow expels plasma through the output hole of the cylindrical tube forming a plume about 2-6 mm in length, as a function of experimental conditions.

A PIN photodiode Hamamatsu S5972 [18], PD, with maximum sensitivity at 800 nm, placed near the plasma source output hole, is directed normal to the plasma plume ejection direction. Its role is to monitor infrared optical emission of the plasma plume. The photodiode PD electrical signal is amplified and filtered, the resulting voltage U_{pd} representing a measure of the plasma plume state. Because infrared optical emission exhibits fluctuations in time, the $R_f C_f$ circuit (time constant $\tau_f \simeq$0.4s), acting as a low pass filter, was inserted at the output of the photodiode amplifier (PDA). The whole setup is controlled by a personal computer PC. For this purpose a specific software application has been developed. The frequency f and excitation

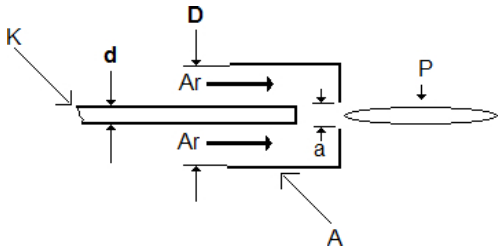

Fig. 3 – Schematic drawing of the plasma source mechanical layout (not in scale). A-anode; K-cathode; P-plasma plume.

voltage U_e on/off switching is controlled by means of LFG which has a USB connection with the PC. The analog-to-digital conversion of voltages U_1, U_2 and U_{pd} are performed by a general purpose acquisition board (GPAB). An adapter circuits AC consisting of voltage dividers and inverter amplifiers converts U_1 and U_2 voltages lying in the range -100V to -1000V into the U_{d1} and U_{d2} voltages lying in the range 0.49V to 4.9V, admissible to be applied to the GPAB inputs. Current discharge I_{dc} is calculated by the software application as: $I_{dc} = |U_2 - U_1|/R_b$.

3. EXPERIMENTAL RESULTS

The effect of the high voltage pulses on the plasma plume state, after that is initiated, has been investigated. To monitor plasma plume state two parameters have been considered:

- dc current I_{dc}
- infrared optical emission of the plasma plume expressed by U_{pd}.

Time variation of the I_{dc} (discharge current) and U_{pd} if high voltage pulses are switched on/off has been recorded. The two graphs correspond to $|U_{dc}| \approx 495V$ (Fig. 4) and $|U_{dc}| \approx 590V$ (Fig. 5), respectively. If applied dc voltage ($U_{dc} = U_1$) is lower than a threshold value (Fig. 4), it can be seen that plasma plume optical emission follows the existence of the high voltage pulses train. When high voltage pulses are interrupted, plasma plume vanishes. If applied dc voltage is greater than the threshold value (Fig. 5), a stable plasma plume continues to exist for at least several tens of seconds. Note that discharge current I_{dc} does not describe accurate plasma plume state. In Fig. 4 spike of the discharge current (denoted by CS) can be observed in the absence of plasma. Its existence is due to parasitic discharges occurring inside plasma source. For given electrodes geometry and experimental conditions, the lower value of the dc voltage, observed experimentally, for which plasma plume is still stable after the high voltage pulses cease, is about 530V.

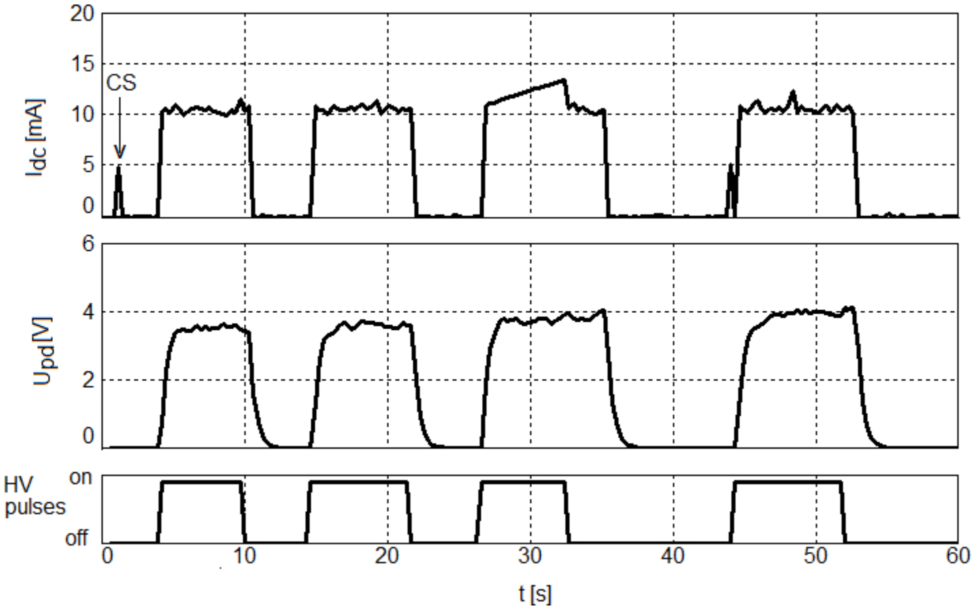

Fig. 4 – Time variation of I_{dc} and U_{pd}, if $|U_{dc}| \approx 495V$. Experimental conditions: $R_b = 3k\Omega$, f=100Hz, T_{on}=1ms, U_g=3.5V.

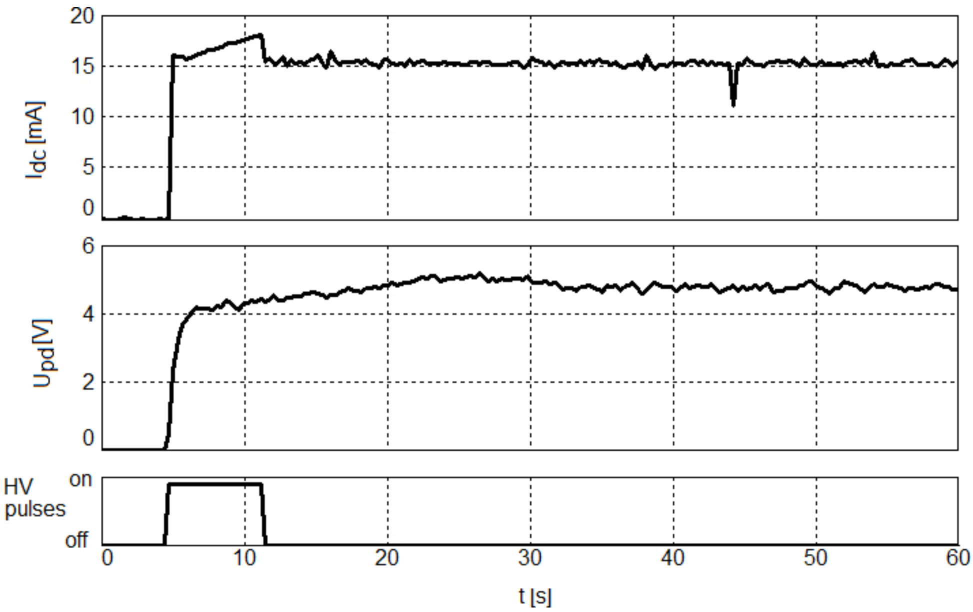

Fig. 5 – Time variation of I_{dc} and U_{pd}, if $|U_{dc}| \approx 590V$. Experimental conditions: $R_b = 3k\Omega$, f=100Hz, T_{on}=1ms, U_g=3.5V.

4. DISCUSSION AND CONCLUSIONS

According to the experimental results, after the plasma plume is initiated, for dc voltage greater than a certain value the electrical discharge continues after the high voltages pulses are interrupted. The plasma plume state was observed simultaneously, optically, by measuring infrared optical emission, and electrically, by calculating the discharge current, respectively. Electrical method is simpler to implement. No additionally mechanical accessories are necessary. However this method is prone to the errors. In some cases, parasitic discharges occurs inside plasma source, so that a significant I_{dc} could exist in absence of an external plasma plume. Optical method is more accurate. Instead, the complexity of the plasma generator, both electrically and mechanically, increases. The two methods can be combined, to detect operating anomalies or electrical failures (shortcuts) of the plasma generator. Based on these observations, as a further work, a procedure aimed to optimize the operation of the high voltage pulse generator can be devised. If plasma plume is in a normal state, meaning that its optical emission is above a threshold value, then high voltage pulses train is switched off. If plasma plume tends to vanish then high voltage pulses train is switched on.

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