Power supplies for non-thermal atmospheric pressure plasma

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Abstract: Evolution of power supplies for low current gliding arcs is considered. Advantages and disadvantages of a classical scheme with ballast resistors are discussed. It is shown that high-voltage power supplies with the high-frequency oscillation of the unipolar voltage allow transferring energy to a gliding discharge rather effectively and this is important for practical applications.

Keywords: Power supplies, non-thermal atmospheric pressure plasma, gliding arc

1. Introduction

LDS Technology Consultants, Inc. provides engineering and other services for client companies which develop and sell non-thermal plasma technologies and devices for use under atmospheric pressure. Therefore, we, as well as many other experts in this area, are quite interested in the state of the art of the technology of power supplies for non-thermal, atmospheric-pressure plasma. This paper presents an analysis of the trends and opportunities in this field.

Low-pressure plasma applied in microelectronics and optics (magnetron sputtering, etching, chemical vapor deposition, etc.) is based on very different power supplies, and power efficiency of those power supplies is largely immaterial from the standpoint of the final product cost. Therefore, we are not going to analyze this field as well as the field of big power supplies for metallurgical applications. Thermal plasma power supplies for welding and plasma cutting are closer to our field, although they are already very specialized and usually cannot be used for new applications.

Over recent years, significant interest has appeared for use of cold (Dielectric Barrier Discharge – DBD, corona and pulsed corona) or “warm” [1] (sometimes called “transitional” [2] or “intermediate” [3]) atmospheric pressure plasma (gliding arc, low current high voltage discharge, microwave discharge) for treatment and sterilization of water, air, exhaust gases, different surfaces, and for biomedical applications. Many researchers and plasma equipment users from various disciplines involved in these activities lack the relevant plasma or electricity-related background. For them, plasma is just a new tool in their areas of interest. In our view, this is a good trend insofar as plasma technology has found its customers. Because there is a demand from such customers, a supply of plasma systems and power supplies for them has appeared also. There are companies that offer and produce such plasma systems and power supplies in small quantities or uniquely customized.

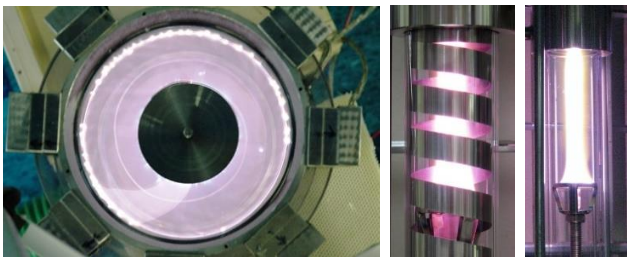
2. Evolution of power supplies for gliding arcs

Let’s consider the evolution of power supplies for gliding arcs or gliding high-voltage low-current discharge. Gliding arc (GA), earlier known as Jacob’s ladder [4], became very popular in 1990-s after publications of A. Czernichowski and co-authors [5, 6]. In the beginning, for research purposes, simple power supply schemes were used [4, 7] that include a general-purpose high-voltage DC power supply and a ballast resistor. This approach allowed for the study the discharge physics “independently” on the power supply using simple models and assumptions.

The power supplies with ballast resistors have a major drawback: the power losses are very high. GA discharge consumes 50% of the power provided by the power supply at the end of the GA development cycle [7], and then it dies out very quickly. At the beginning of the development cycle, GA consumes an even smaller portion of the available power, and the rest of the power releases as heat at the ballast resistor. Moreover, these ballast resistors (usually variable) are so bulky that their dimensions are larger than those of power supplies. The high voltage variable ballast resistors are not commercially available and usually, they are “home-made” by the lab personnel, and therefore are not very safe and reliable. The authors have experience working with such systems. Universal Voltronics (10 kV, 1 A, positive or negative) or Glassman High Voltage, Inc. (SH series, 15 kV, 530 mA) power supplies were combined with home-made high-voltage variable ballast resistors. Fig. 1 show the dimensions of the 8 kW Glassman power supply and a variable resistor box.

Fig. 1. Glassman High Voltage, Inc. 8 kW – 15 kV power supply and a home-made variable resistor box with a mounted high-voltage probe.

Several GA systems were developed that allow keeping the length of the discharge close to its maximal value, for example by rotating the discharge in a magnetic field [2, 3] or by "catching" it to circular electrodes in the reverse-vortex ('tornado") configuration [3]. Fig. 2 demonstrates examples of such discharges. However, even maximally elongated discharge in "overshooting" mode [7] consumes only about 50% of the available power [2].



a b c

Fig. 2. Gliding discharge of constant length rotated by a magnetic field (a) and by the reverse-vortex ("tornado") flow (b, c) elongated by a spiral electrode (a, b) or mechanically by the electrode motion (c).

There were attempts to power the constant length gliding discharge without a ballast resistor using a power supply in a current stabilization mode (e.g. Glassman High Voltage, Inc., SH series power supply has this mode). Unfortunately, the reaction time of PS is too long in comparison with the discharge instability development time even when a high-voltage inductance was included into a circuit. Fig. 3 demonstrates an oscillogram of operation in such a current-stabilization mode.

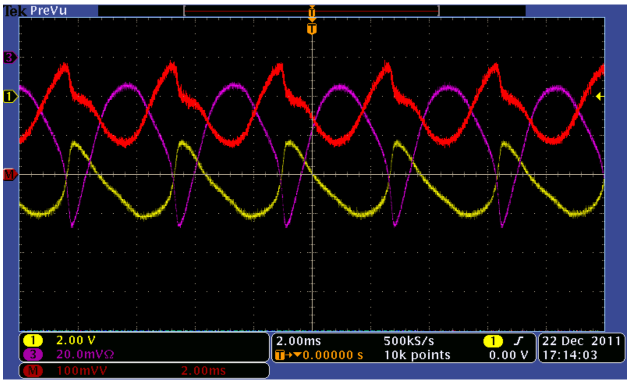


Fig. 3. Operation in a current-stabilization mode: voltage – yellow (2 kV per division); current – purple (0.2 A per division); instantaneous power – red (1 kW per division).

This regime is detrimental for the power supply parts because of their overheating, therefore we were forced to use the ballast resistors again (Fig. 4). Fig. 4 shows the advantage of using the constant voltage PS with a ballast resistor for the study of the discharge properties. It is possible to see that the discharge length is not really constant because of sticking of the electrode spots on the circular electrodes. As the result, the discharge elongates a little, then shortens abruptly after the electrode spot "jump" to a new place.

Significant power losses and bulky equipment can be acceptable in a laboratory study of a discharge or plasma-chemical process, but not for practical applications. Therefore, when an opportunity appeared to use the gliding discharge for flame stabilization [8], we formulated a requirement for development of a power supply that can work without a ballast resistor and can transfer most of the power to the discharge. According to the available information, the first such power supply was developed by Quinta, Ltd (Moscow, Russia) [8]. It seems that the characteristics of this power supply are yet unpublished. It is known that this PS was designed to support constant average power in a discharge, while the unipolar current and voltage oscillated with high frequency. These high-frequency oscillations did not change the discharge behaviour but allowed to stabilize power using reactive circuit elements, capacitors and/or inductances, without Ohmic losses.

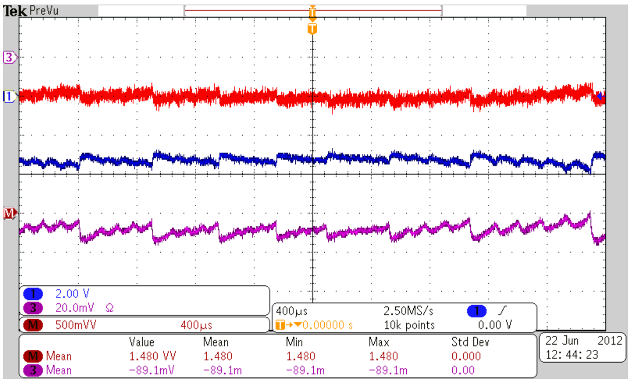


Fig. 4. Oscillogram of a constant length discharge with constant voltage PS and a ballast resistor: voltage – blue (2 kV per division); current – purple (0.1 A per division); instantaneous power – red (0.5 kW per division).

3. Modern solutions for gliding arcs

Recently our company, LDS Technology Consultants, Inc., received a work order for development of a hand-held plasma jet generator with power 1-2 kW. It should produce high-speed air plasma jet with an average temperature of about 1000 K and have a long service-free operation. We decided to develop this generator on the basis of low-current high-voltage discharge inside the reverse vortex flow. The reverse vortex should allow operation without additional cooling and the low current should ensure a long lifetime of thermo-chemical cathodes. We ordered a power supply from Advanced Plasma Solutions Co. (APS) that produces small customizable power supplies, particularly for gliding discharges. The major requirement formulated for the power supply were the following: unipolar current (for use of thermo-chemical cathode), high voltage (15 kV) for discharge ignition, and continues adjustment of power in the wide range of 400-2,000 W with the average current value not exceeding 2 A. Oscillation frequency of voltage and current should be rather high – to avoid influence on the discharge stability and not cause additional ignition and dying-out events, which are the most detrimental for electrodes.

During the collaborative development (it is not possible to finalize the development of such power supply without matching it with the discharge device), APS tested two types of the power supply: (1) – with direct ignition when the initial breakdown is caused by the no-load high voltage of the same circuit that supports the discharge existence, and (2) – with a separate ignition circuit that is responsible for the discharge initiation and connected in parallel with the major power-providing circuit of the relatively low voltage (such a scheme was realized in the early gliding discharge works [4, 5]). Portions of the digitized oscillograms of the plasma device operation (Fig. 5) with these power supplies are provided in Figs. 6 and 7.

Fig. 5. Hand-held 2 kW high-speed plasma jet generator.

Fig. 6 shows that the voltage modulation does not change the gliding nature of the discharge: it elongates by the motion of the anode spot to the nozzle and the voltage amplitude grows. When the voltage amplitude reaches 2.5 kV, a new breakdown happens between the discharge channel and the nearest anode point, and the voltage amplitude drops to 600 V. After that a new discharge elongation starts.

Fig. 7 shows that the power supply with the separate ignition circuit and relatively high average power (2 kW) allows stabilizing the discharge length in our device at a maximum when the anode spot circles on the nozzle exit. As the voltage amplitude is lower than with the direct ignition power supply, this voltage does not cause new breakdowns between the discharge channel and the anode. To reach this relatively high power with relatively low voltage, it is necessary to use higher current settings.

So far, we don't have experimental data that can show which of these two power supplies can provide a longer lifetime of our plasma device. From the general standpoint, the lower average current should provide lower electrode erosion rate despite the low-frequency power oscillation related to the periodical discharge shortening. This should be especially true for the anode; however, some erosion acceleration can take place in the area of the secondary breakdowns. We did not observe any "sparks" in the plasma jet that can provide evidence of the intense electrode erosion with any of these power supplies. The efficiency of both power supplies was on the level of 75-80%.

Thus, high-voltage power supplies with the high-frequency oscillation of the unipolar voltage allow transferring energy to a gliding discharge rather effectively.

4. References

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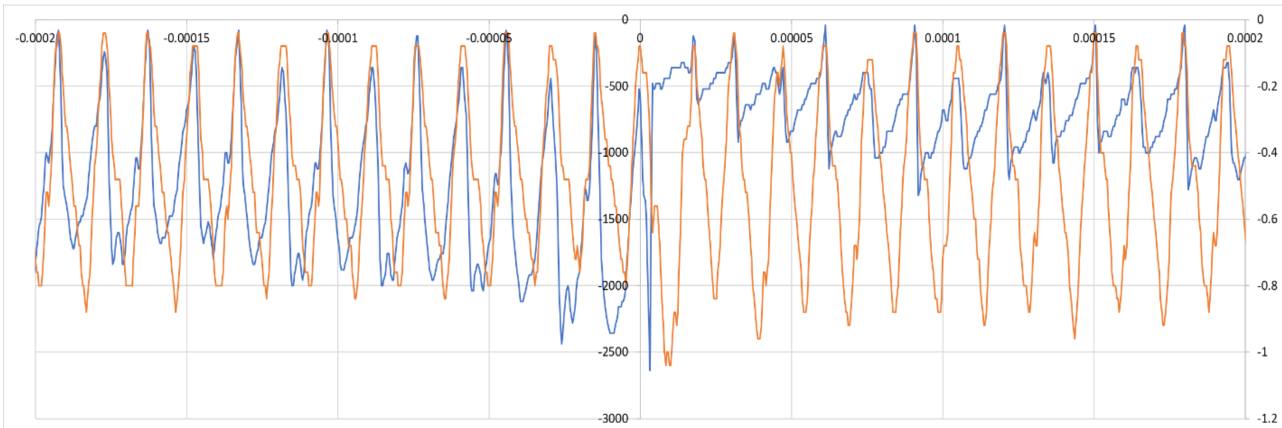

Fig. 6. Time variation of current (yellow, the right axis in Amperes) and voltage (blue, the central axis in Volts) of the plasma device with the direct ignition power supply.

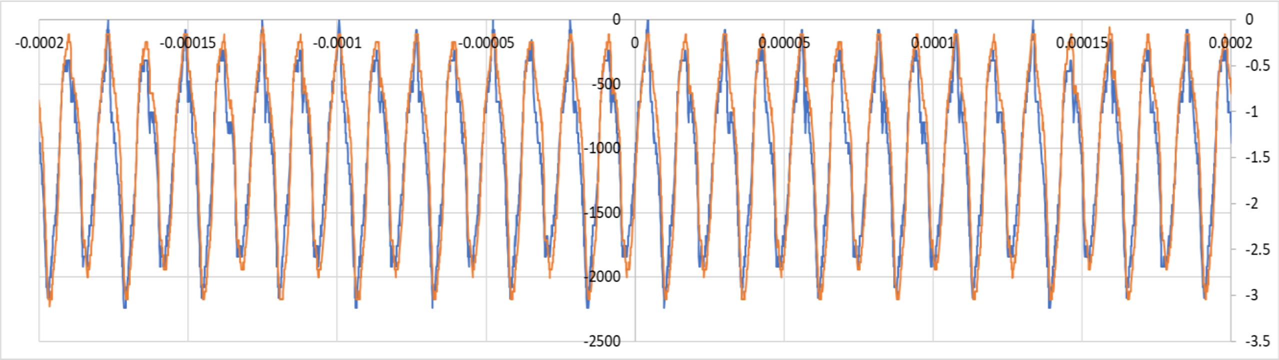

Fig. 7. Time variation of current (yellow, the right axis in Amperes) and voltage (blue, the central axis in Volts) of the plasma device with a separate ignition circuit.