

Asymmetric Bipolar Plasma Power Supply to Increase the Secondary Electrons Emission in Capacitive Coupling Plasmas

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Abstract—Power supplies have played crucial role to improve and extend plasma applications. Several dc, pulsed, and radio frequency (RF) stabilized power supplies have been developed over a wide range of frequencies and voltage waveforms. However, the influence of voltage waveform on the plasma densification, mainly due to the secondary electrons emission from the electrodes, has not been quite explored. This paper proposes an asymmetric pulsed bipolar power supply, adjustable in frequency, amplitude, pulsewidth, and number of pulses for generation of cold plasmas. Short period positive pulses, between longer negative pulses, increase greatly the secondary electron emission from the electrodes and, consequently, the plasma ionization rate. Short pulses (ns) are obtained by the phase shift between each carrier, and the high-intensity pulses are obtained by cascading the cell submodules in a half-bridge cascade topology, using a modular half-bridge converter configuration. The intensity of the positive and negative pulses can be varied independently. There is no unintended dc voltage level between the electrodes, which appear in RF plasmas. The plasma generated in this way is free of electric arc and can be kept stable within a broader range of operating parameters, mainly the voltage and the working gas pressure.

Index Terms—Modular multilevel converters (MMCs), plasma sources, pulsed-power supplies, secondary electrons emission.

I. INTRODUCTION

PLASMA is an ionized gas, that is, a fluid containing neutral atoms or molecules, free ions, and electrons, whose luminescence is caused by quantum effects [1]. The presence of these charged species makes the medium chemically more active, besides allowing the energy control of these particles using electromagnetic fields [2]. Low-temperature plasmas have been increasingly used in various technological areas, such as: semiconductors for computational systems, films for photovoltaic cells and photocatalysis, surface treatment of

materials, treatment of polluting gases, activation of chemical reactions, functionalization of surfaces, and deposition of thin and thick films [3], [4].

Plasma can be generated in two main ways: “capacitive coupling plasmas” [5] and “inductive coupling plasmas” [6].

The subclassifications depend on the waveforms of the applied voltage, among which can be mentioned: radio frequency (RF) plasmas [7], continuous dc and dc pulsed plasma [8], [9], microwave [10], and ac pulsed plasma [11]. Power supplies that can increase the ionization rate in cold plasma, in a controlled manner, is the key issue to expand the most diverse industrial applications of plasmas and to obtaining better or new results. In the last two decades, it has been developed many different power supplies including those with RF, stabilized dc voltage, and pulsed ones. Among them, the high-power impulse magnetron sputtering became popular for producing a high ionization rate of sputtered atoms from the target, in films deposition applications [12]–[17]. There is a challenge for developing topologies involving high voltage and current as well as high switching frequency which has been pursued over the years. Conventional power supplies do not have these characteristics due to technological difficulties, mainly due to the availability of switches that can handle high-voltage and high-current values concomitantly with short switching times. Looking to the bases, the Marx generator can be used to generate high-voltage pulses with extremely high-current slopes (picosecond or nanosecond), obtained by charging capacitors in parallel and discharging them in series. It is possible to generate pulses up to 100 kV or even further, where spark gaps are usually used to switch the circuit in a pulsed forming line configuration, with series impedance that helps insulate oscillations reflected from the load [18].

On the other hand, the Marx Generator is not suitable to generate long pulses due to the inherent discharge of its internal capacitors. Cassel [19] proposes to compensate the output voltage droop by using an auxiliary circuit that allows extending the pulsewidth to around 100 μ s with a 3% discharge. However, prolong the pulse time is not a simple matter. New circuits were developed to increase the flexibility in the output waveform generation. For example, in [20] and [21], a flexible circuit was presented that allows positive and negative pulse generation, adjustable duty cycle, associated with adjustable frequency and relaxation time. One drawback of this circuit is the need of a relaxation time during

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the charge of the internal capacitors, which limits the flexibility of the pulse generation (i.e., bipolar generation without zero level). Similarly, reference [22] shows a bipolar solid-state Marx generator that uses semiconductor switches and inductors to increase the efficiency in an H-bridge configuration, including equal capacitors charges, with high-output voltage slopes (rise and fall). However, it requires the use of high-voltage switches in the H-bridge, which usually have long commutation times, limiting the output frequency. The positive and negative pulses generated in this way need to be equal because this generator uses the same voltage source in both polarities.

In [23], an interesting circuit was presented that generates high voltage narrow positive and negative pulses. One drawback is the difficulty to control the synchronism among all cascaded switches to avoid a possible over voltage. Another is the absence of a balance voltage circuit to ensure the same voltage level in both split capacitors of the bus. Therefore, the bipolar output pulses also cannot be varied in asymmetric way, as desired in this paper for the proposed method of plasma generation.

A modular multilevel converter (MMC), in half-bridge H configuration, presented by Elserougi *et al.* [24], uses a grouping of cell submodules to obtain high-voltage from low-voltage power, using a sensorless voltage balancing technique to assure the same voltage in each submodule. The use of commercial nonspecial components is a great advantage. However, the converter needs two bulky capacitors to form the splitted dc bus with a midpoint connection and the peak of the generated bipolar pulses will be half of the available total voltage, due to the pulsewidth modulation technique adopted [25]. The use of an arm inductance between the load and the link capacitor formed also limits the current derivative slope. Alternatively, reference [26] and [27] show a grouping of cell submodules for the formation of single-phase legs, derived from the Marx generator, without the use of inductors or dissipative elements. The voltage over each cell capacitor is balanced by using a vector algorithm, afforded by a series of diodes between adjacent cells, enabling multilevel pulse generation without voltage or current capacitor measurements (error less than 10%).

The MMC converter presents advantages as, for example, the redundancy, greater tolerance for parasitic inductances (inherent to the construction of high-voltage converters), and easy scalability. The absence of central components and floating sources is a great advantage when considering that is possible to conjure a wide range of applications to meet demands at different levels of power and voltages from standard structures.

In this paper sets out to investigate a new power supply using half-bridge cascade topology, with a reduced number of switches, in a modular half-bridge converter configuration using cell submodules, similar to those observed in [28]. Beyond the reduced cost and simple design, its bipolar configuration, with short period of positive pulse and longer negative pulses, can produces high emission of secondary electrons from the cathode. Then, this power supply can greatly increase the plasma ionization rate. It is possible also generate symmetrical or asymmetrical pulses of short or long duration with

voltages up to tens of kV and frequencies up to hundreds of kHz. A prototype of ± 2.5 kV and up to 500 kHz was built for studies of plasma generation. The short-duration pulses can be obtained, for example, by a phase lag shift between each carrier, and the high-intensity pulses are obtained by cascading the cell submodules. It is possible alternate between short and intense positive pulses with nonintense and long negative pulses, and vice versa, with short and intense negative pulses with nonintense and long positive pulses, depending on the need of each application.

Moreover, the number of pulses and rest times can be adjusted between each pulse, as well as the rise and the fall time, frequency and duration of each pulse. Sections II–IV present the proposed converter, the method used to generate the voltage pulses, a modulation example, the main equations, the output waveforms, the circuit diagram, and a photograph of the prototype. It is also shown results of current and voltage in plasma generated with the asymmetric bipolar plasma power supply (ABiPPS), whose were compared with the results of a commercial power supply.

II. PROPOSED CONVERTER TOPOLOGY

A. Multilevel Converter

In order to obtain a bipolar voltage pulses with the possibility of generating different positive and negative amplitude peaks applied to the plasma, a half-bridge connection was used to form legs with individual power supplies. Fig. 1 shows an illustration of the converter configuration, with “ n ” levels on each leg. At the base, the legs are interconnected through an M point, which can be used for voltage measurement. At the top, the circuit is interconnected through the plasma generated between the electrodes. One of the electrodes, usually the chamber wall, is grounded. The measured signals are isolated and conditioned in order to be acquired by the reading ports of a central control unit (CCU). The CCU can actuate on the switches of each submodule, after performing the calculation of the control routines, based on the parameters sent by the soft panel interface. This configuration enables the use of single low voltage submodules, allowing the construction of high-voltage and high-frequency converter. Each submodule can be controlled for supplying “null” voltage (top and bottom switch opened), level “high” (top switch closed), or level “low” (bottom switch closed), according to the desired output result, as shown in Fig. 1. In each submodule, the voltage difference between the levels “high” and “low” is a fraction of the total leg output voltage. Due to the phase shift method used, the width of the output voltage pulses can be greatly reduced.

B. Modulation and Theoretical Waveforms

Fig. 2 shows a diagram of symmetric pulsewidth modulation (PWM) with “ n ” levels used for the output pulses generation. A modulating “reference” is compared with each triangular waveform, resulting in the T_H and T_L pulses of each submodule. In addition, the short-circuit protection delays between the conducting states in the T_R -up and T_F -down transitions are configurable. It should be noted that there is

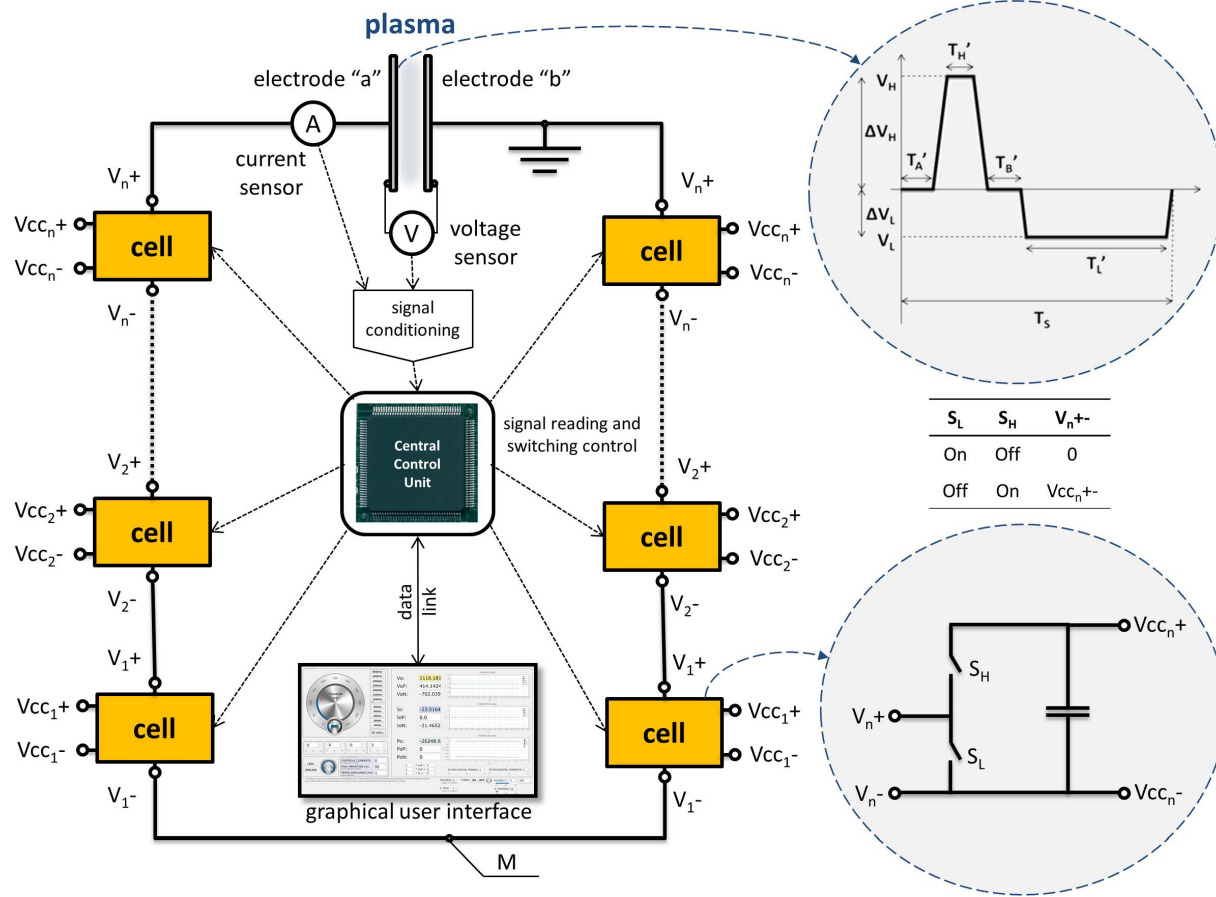


Fig. 1. Converter power circuit configuration (M: medium point that can be used for measurement).

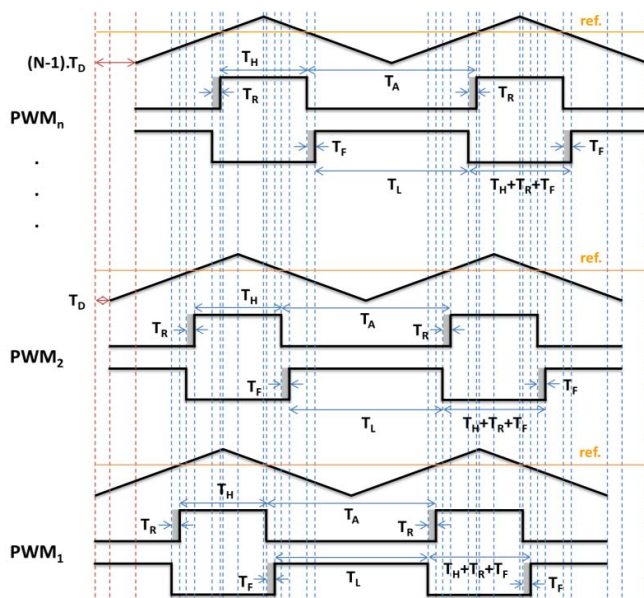


Fig. 2. Symmetric triangular modulation with "n" levels.

a delay T_D between the modulations of each power block of each leg. For “n” blocks, the total delay will be $(n - 1) \cdot T_D$. The soft panel interface allows the user to perform the parameterization to completely configure the waveform applied between the electrodes: the positive pulsewidth, negative pulsewidth, time T'_R between each positive and negative

pulses, time T_C between each negative and positive pulses, frequency (as a result of T'_A , T'_H , T'_B , and T'_L), positive amplitude V_H , and negative amplitude V_L . It is important point out that it is possible apply different PWMs for the positive and negative pulses generation, allowing the rest time elimination (or obtaining an extremely reduced one).

Short positive pulse (for example, 10 ns) produces intense emission of secondary electrons from the electrode. If it is associated with quick polarization inversion, these secondary electrons are accelerated toward the glow discharge and, therefore, it increases the ionization rate in the plasma. For this purpose, for example, two procedures outlined by Fig. 2 could be implemented: one for the positive pulses and another for negative ones. The appropriated phase shift modulation and the interlocking time delay in each leg must be carefully carried out.

C. Generation of Short Pulses

As previously discussed, the main purpose of the technique is to obtain high-voltage short-positive pulses followed by long pulses with low voltage. The hindrances recline on positive pulse generation, where the challenge is to defeat the inherent delay between receiving the command signal and effectively carry out a high-voltage state change in the power circuit output, as fast as possible. Other relevant effect to be considered is the short pulses suppression present in the gate driver circuits that limit the minimum on-time of

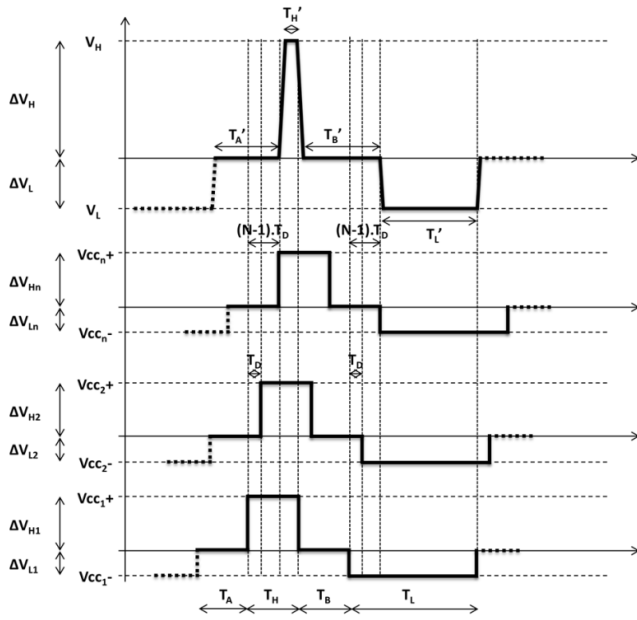


Fig. 3. Voltage pulses profile at the output of the converter (short or long, according to the duration and the delay between the pulses of each level).

the switches. To overcome these drawbacks and ensure short pulses generation it was proposed a strategy of phase shift among the gate pulses of each submodule. Thus, the output pulse voltage is only applied to the plasma when the last submodule is turned ON. On the other hand, when the first submodule is turned OFF, the voltage output decrease ensuring a short pulse operation. Fig. 3 shows the sequence of steps necessary to obtain the output pulses for a converter with “ n ” submodules. The following equations can be written:

$$T'_A = T_A + N \cdot T_D \quad (1)$$

$$T'_B = T_B + N \cdot T_D \quad (2)$$

$$T'_H = T_H - N \cdot T_D \quad (3)$$

$$T'_L = T_L - N \cdot T_D \quad (4)$$

$$V_H = V_{cc1+} + V_{cc2+} + \dots + V_{ccn+} \quad (5)$$

$$V_L = V_{cc1-} + V_{cc2-} + \dots + V_{ccn-} \quad (6)$$

In each equation, by controlling the parameters values in the right makes it possible to control the global variable in the left. In this way, the voltage pulse to be applied to the load (plasma) will be very short in time, reaching values in the order of magnitude of nanoseconds. This period can be shorter if used other technologies (for example, GAN), allied to the held of a state of the art processor and isolated optical drives.

III. ANALYSIS AND DESIGN OF THE PROPOSED CONVERTER

The design and assembly of a pulsed source, with positive and negative pulses adjustable in an independently way, configurable in frequency, amplitude, and duty cycle was performed to validate the new method for densification of nonthermal physical plasmas proposed. As previously stated, the possibility of adjustment with several degrees of freedom provides flexibility in the generation of plasmas, allowing the

TABLE I
DATA FOR THE CONVERTER DESIGN

Parameter	Value
Output power (P_o):	5kW
Maximum output voltage (V_H):	+2000Vdc
Minimum output voltage (V_L):	-700Vdc
Number of submodules (n):	5
Max. submodule dc bus voltage (V_{cc}):	+400Vdc
Input grid voltage (V_{RST}):	380Vrms, 60Hz
Positive Nominal Duty Cycle (D):	5%
Frequency (f):	0 up to 500kHz
Minimum Pulse Width:	0.5us

selection of parameters to generate high-energy electrons and, consequently, high rate of ionization. Table I shows the main specifications for the power design of the proposed converter.

A. Mathematical Analysis and Design Results

To perform the mathematical analysis of the converter, it was considered the worst operation case, when the positive and negative pulses are complementary. To simplify the design of the converter the load was considered resistive. In this case, the average voltage in the converter output can be calculated by

$$\overline{V_{OUT}} = V_H \cdot D + V_L \cdot (1 - D) \quad (7)$$

where D is the positive nominal duty cycle.

The equivalent load resistance can be calculated by

$$R_o = \frac{\overline{V_{OUT}}^2}{P_o} \quad (8)$$

The peak current in the upper switches of side “A” and lower switches of side “B” can be expressed as

$$I_{SWHpk} = \frac{V_H}{R_o} \quad (9)$$

The average and rms current in the upper switches of side “A” and lower switches of side “B” can be calculate with (10) and (11), respectively,

$$I_{SWHav} = I_{SWHpk} \cdot D \quad (10)$$

$$I_{SWHrms} = I_{SWHpk} \cdot \sqrt{D} \quad (11)$$

The peak current in the lower switches of side “A” and upper switches of side “B” can be expressed as

$$I_{SWLpk} = \frac{-V_L}{R_o} \quad (12)$$

The average and rms current in the lower switches of side “A” and upper switches of side “B” can be calculate with (12) and (13), respectively,

$$I_{SWLav} = I_{SWLpk} \cdot (1 - D) \quad (13)$$

$$I_{SWLrms} = I_{SWLpk} \cdot \sqrt{(1 - D)} \quad (14)$$

Table II shows the summary of the calculations-based in the mathematical analysis and specifications. Table III shows the main selected components, including those for the command circuit. The same power switches were used on legs “A” and “B” in order to allow the full power operation on both output polarities.

TABLE II
CALCULATED RESULTS

Parameter	Results
Average output voltage (V_{OUT})	-565V
Equivalent load resistance (R_0)	63,8Ω
Peak current in the upper switches of side "A" and lower switches of side "B" ($I_{SW_{h_{pk}}}$)	31,3A
Average current in the upper switches of side "A" and lower switches of side "B" ($I_{SW_{h_{av}}}$)	1,6A
RMS current in the upper switches of side "A" and lower switches of side "B" ($I_{SW_{h_{rms}}}$)	7,0A
Peak current in the lower switches of side "A" and upper switches of side "B" ($I_{SW_{l_{pk}}}$)	11A
Average current in the lower switches of side "A" and upper switches of side "B" ($I_{SW_{l_{av}}}$)	10,4A
RMS current in the lower switches of side "A" and upper switches of side "B" ($I_{SW_{l_{rms}}}$)	10,7A

TABLE III
SELECTED COMPONENTS (MAIN)

Component	Part Number	Manufacturer
Power switches	AUIRGP50B60PD IGBT 600V/33A	Infineon
Rectifier bridge	SKD30/08A1 Diode 800V/15A	Semikron
DC Link Capacitors	B43504 snap-in 470uF / 450V	Epcos
Digital signal processor (DSP)	TMS320F28335	Texas Instruments
IGBT Gate Drivers	DRO100D25A	Supplier

B. Submodules Implementation

Fig. 4 shows the power circuit of the left leg of the prototype assembled for testing the converter proposed. (The right leg is symmetrically identical.) The rectifiers are powered by three-phase circuits in order to reduce the ripple on the dc link. Each leg comprises a voltage regulators (varivolt) that feeds a galvanic isolated voltage transformer, used to avoid short-circuit between each submodule, allowing the peak amplitude adjust individually (left leg produces the positive pulses and right leg produces the negative ones). The power supply used (varivolt with isolated transformer) could be replaced by an electronic one, but this was not the main purpose of the work and there was no such equipment available in the laboratory when the project was carried out.

C. Prototype Implementation

Fig. 5 shows the view of the prototype built, detailing the cell submodule (including the rectification, filter, protections, drives, and switches). The digital signal processor (DSP TMS320F28335 from Texas Instruments, Dallas, TX, USA) was used for the process control. The soft panel interface was designed in the Gui Composer Module, from Texas Instruments.

IV. PLASMA STATE

Fig. 6 shows a typical vacuum chamber for plasma generation, with capacitive coupling. The power source is used to

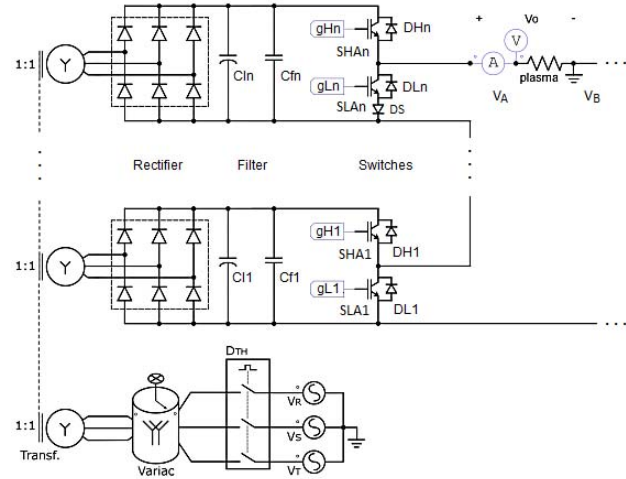


Fig. 4. Power circuit of the prototype assembled one leg: "DTH" represents the circuit brake used for short-circuit protection, "Variac" is a voltage regulator, "Transf." is a galvanic isolated voltage transformer with "1" input and "n" outputs (three-phase), "Cl" and "Cf" are the link capacitor (electrolytic) and filter capacitor (poliester), respectively, "S" represents the IGBTs and "D" the free wheel diodes used. The plasma impedance was represented by a resistance (abnormal glow region).

create an electric field between an anode and a cathode, immersed in a gas, with a pressure typically between 1.3 Pa (10–3 torr) and 1333 Pa (10 torr). Secondary electrons are those electrons emitted from the electrodes due to the bombardment of its surface by electrically charged particles from the plasma (ions and electrons). Secondary electrons are responsible for the maintenance of the plasma, i.e., the transport of the energy supplied by the power supply to the plasma.

The secondary electrons emitted from the cathode pass through the cathode sheath, where they acquire kinetic energy proportional to the potential difference in the sheath. These electrons are accelerated toward the luminescent region of the plasma. About 90% of the electrical voltage applied to the process decays in the region of the sheath (typically in the order of hundreds of Volts). Therefore, these secondary electrons reach the luminescent region of the plasma with high energy, which dissipates through different processes: ionization of neutral atoms, transfer of energy to the local population of cold electrons, and excitation, heating, and dissociation of atoms and molecules of the working gas (e.g., noble gases and molecular gases). Therefore, the control in the emission of secondary electrons is an important tool for the control, generation and maintenance of the plasma state.

In pulsed dc or dc plasmas, the secondary electrons are produced mainly by ion bombardment on the cathode, as illustrated in Fig. 7. However, the yield of the secondary electrons produced by ions that collide with the cathode is very low (typically 0.1 or less for applied voltage potentials of the order of hundreds of Volts). On the other hand, the bombardment of the target (cathode) by electrons increases the emission of secondary electrons. Therefore, if the target (electrode) is bombarded with electrons, it will be possible to increase the plasma density because of the higher emission of secondary electrons, as illustrated in Fig. 8.

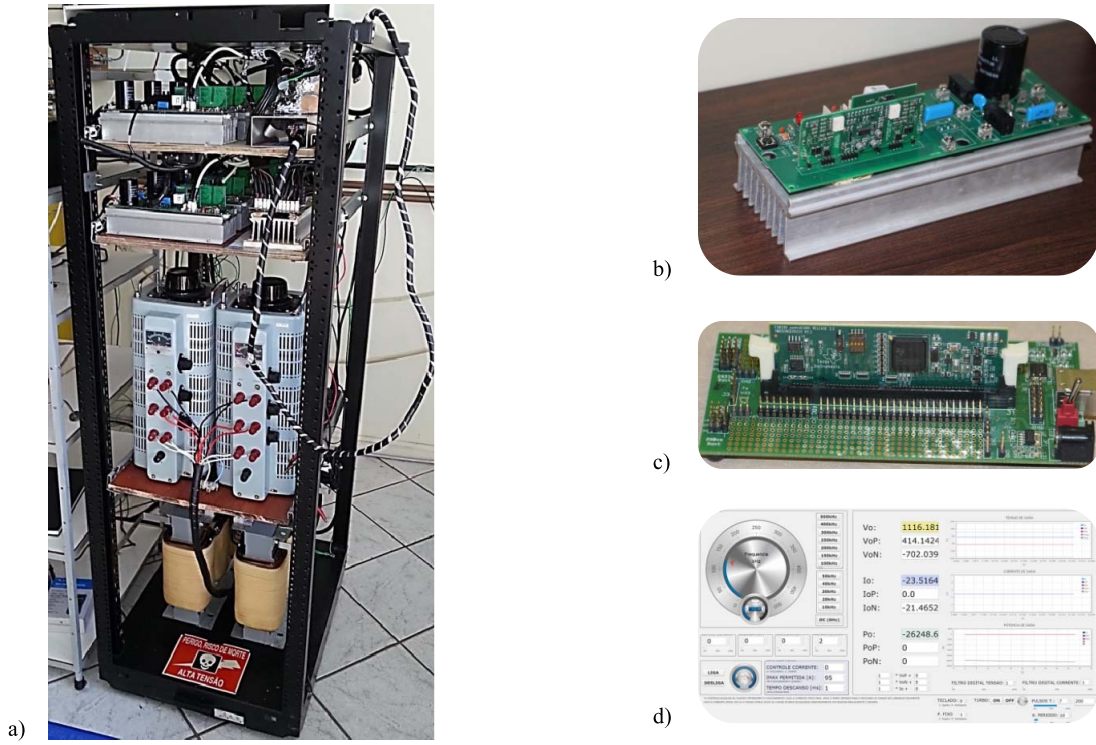


Fig. 5. Implemented prototype of the pulsed bipolar with five submodules. (a) Picture of the rack with the complete solution. (b) Picture of a cell submodule. (c) Picture of the DSP board. (d) Soft panel user interface.

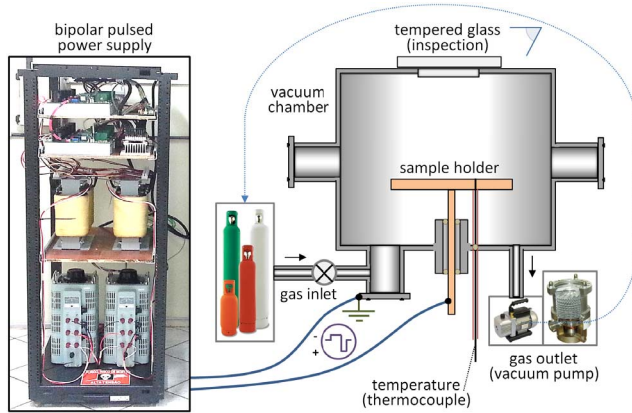


Fig. 6. Illustration of the plasma discharge configuration used.

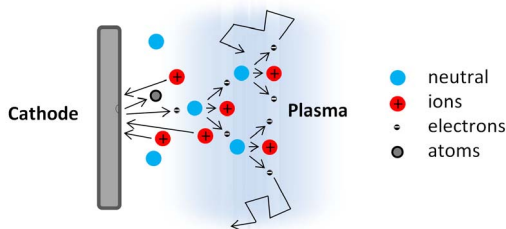


Fig. 7. Electron emission due to ions bombardment.

The positive pulse must be short (in nanoseconds or less, preferably) to keep the plasma close to the metallic electrode. It is very important to point out that the yield δ of secondary electrons emission, due to electron bombardment ($\delta = e/e$) is more significant than yield γ due to ion bombardment ($\gamma = e/\text{ion}$).

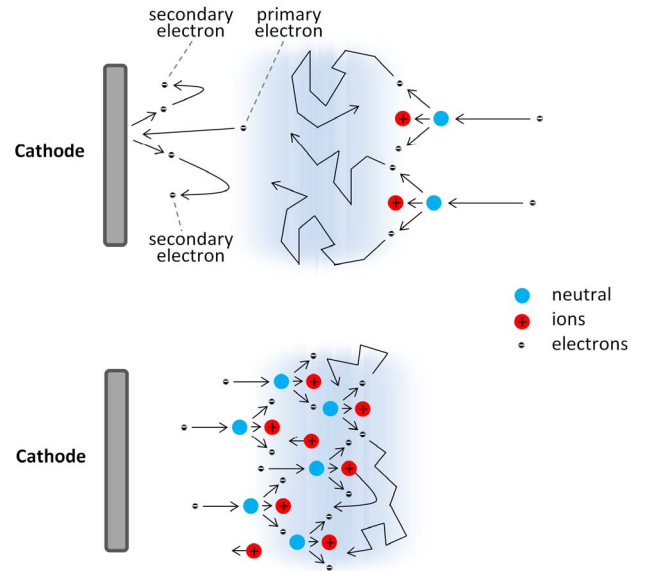


Fig. 8. Electron emission due to electrons bombardment.

For example, for a Ni target, the coefficients of the secondary electron are $\delta = 1.3$ and $e\gamma = 0.15$ (with Ar⁺ and bombardment energy of 500 eV), that is, δ is significantly higher than γ .

V. EXPERIMENTAL RESULTS

A. Output Waveforms

Several experiments were carried out for testing the converter assembled. Fig. 9 shows a typical waveform used for raising the ionization rate, where the positive pulses are

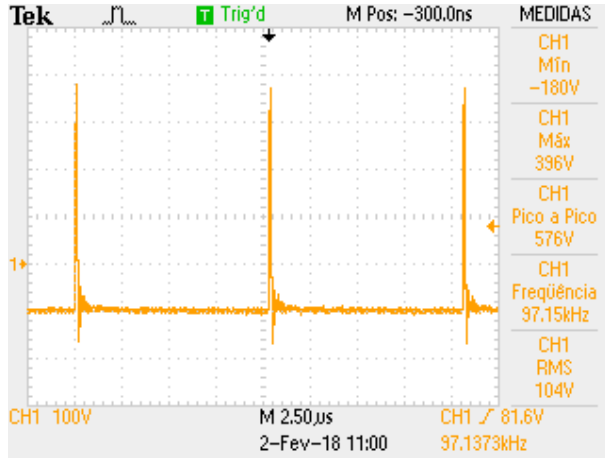


Fig. 9. Example of a voltage pulse configuration (short intense positive pulses interleaved by negative dc level).

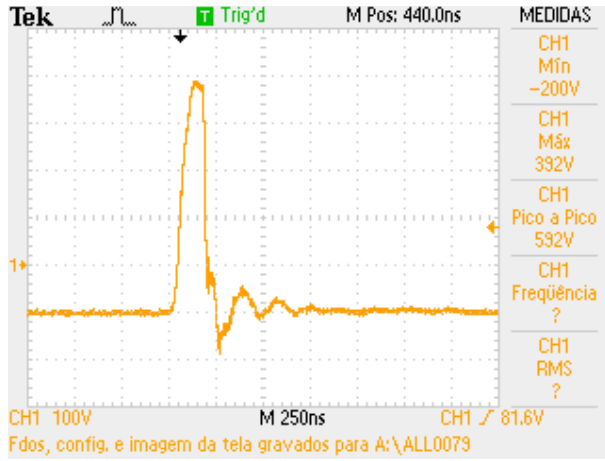


Fig. 10. Detail of the voltage pulse shown in Fig. 9.

significantly higher and shorter than the negative one (measurements with TDS2024 oscilloscope and P5100A voltage probe). Fig. 10 shows a detail of the voltage pulse shown in Fig. 9. The base frequency is ~ 100 kHz, but the positive pulse is very short, as indicated in Fig. 10, with period of ~ 250 ns. As previously mentioned, the positive pulse must be short to maintain the ions and the glow discharge (heavy particles) at the region next to the electrode, during the secondary electrons emission time. Fig. 11 shows another waveform configuration, where there are a pulse train of short and intense pulses followed by a negative bias time. This configuration can be useful to carry out plasma surface treatment when low temperature is mandatory: during the train of intense pulses the plasma glows and during the low negative bias the ions reach the part surface with low energy. For example, with this configuration, it was possible to keep the surface temperature below 100°C . The discrete IGBTs used have low gate capacitances. After consulting the manufacturer, some changes were carried out in the driver circuit in order to allow its operation with higher frequencies. ($Z_b = 3$ and 1 V , $R_{TD} = 0.5\text{ k}\Omega$, and $R_{GA} = 27\text{ }\Omega$). The control software developed allows even to choose the number of pulses applied. Fig. 12 shows in detail an example where nine pulses were selected, reaching a frequency of ~ 500 kHz.

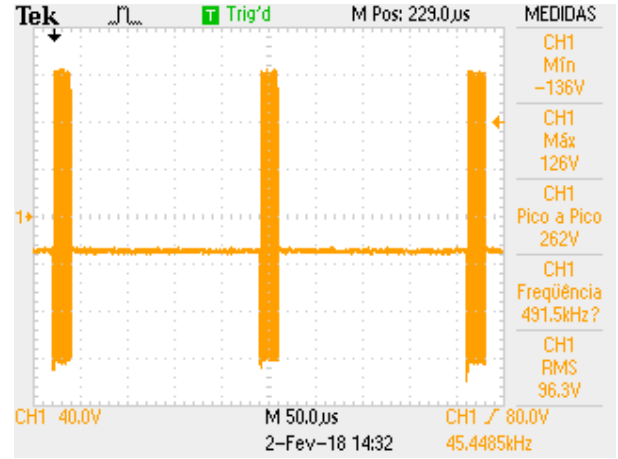


Fig. 11. Example of a voltage pulse configuration (high-intense negative and positive pulses interleaved by negative dc level).

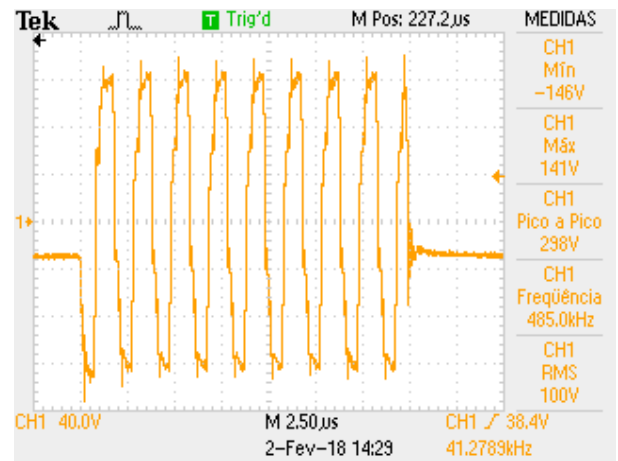


Fig. 12. Detail of the voltage pulse configuration shown in Fig. 11.

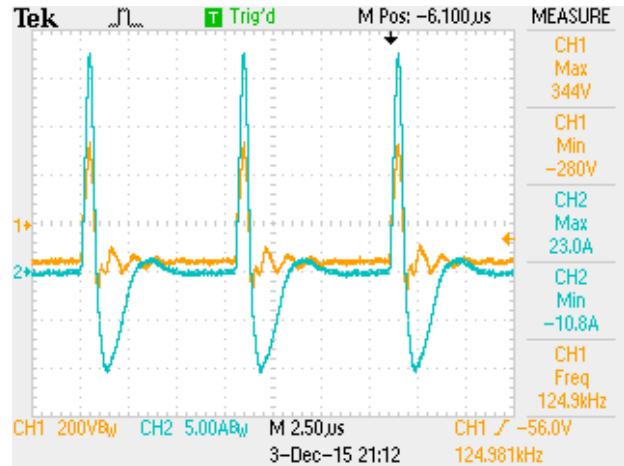


Fig. 13. Voltage and current outputs for an argon atmosphere of 667 Pa (5 torr): negative peak current of -10.8 A (converter developed).

B. Comparison Between the Converter Developed (ABiPPS) and a Comercial Power Supply

Fig. 13 shows the output current and voltage waveform for plasma produced in argon working gas at pressure of 667 Pa (5 torr), with the ABiPPS converter, and Fig. 14 shows the related results with a commercial pulsed-power supply,

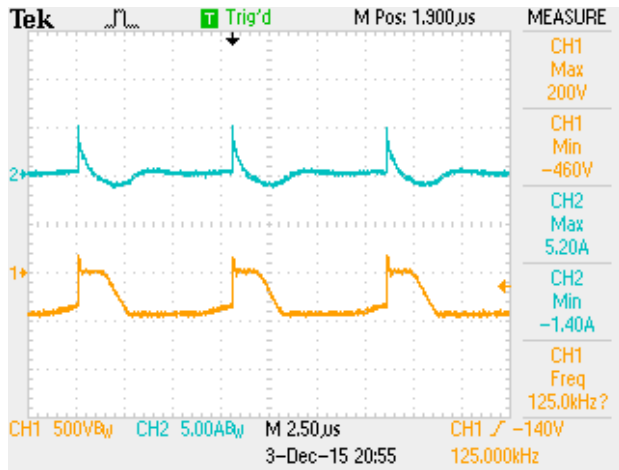


Fig. 14. Voltage and current outputs for an argon atmosphere of 667 Pa (5 torr): negative peak current of -1.4 A (commercial power supply).

in which the positive pulse voltage is fixed in 10% of the negative one.

The measurements were made with TDS2024 oscilloscope, P5100A voltage probe and TCP312A current probe. The baseline of negative pulse voltage, necessary for plasma maintenance, is lower for ABiPPS (-200 V) than for commercial power supply (about -400 V). Besides the lower negative voltage baseline, the current peak-to-peak is from -10.8 to 23 A, for plasma generated with ABiPPS (Fig. 13). Results for commercial pulsed-power supply shown much lower values, from -1.4 to 5.2 A (Fig. 14). This means that the plasma density (electrons and ions density) is significantly higher for the plasma supplied by ABiPPS. In many plasma applications (for example, nitriding and sputtering systems), the main interest is on the cathode effects, that is, when the voltage pulse is negative. In this case, the current increases notably by a factor 7.7 (-10 and 8 A/ -1 and 4 A) that increase the ion bombardment and make more efficient the interaction of the plasma with the surface of the cathode. The current density reached approximately 100 mA/cm² for the 10 -A negative current peaks. This value is considerably higher than the current density values found in discharges with commercial power supplies, which are around 1 mA/cm² for dc mode and up to 10 mA/cm² for pulsed mode. The higher current observed in plasma supplied by ABiPPS is attributed to higher plasma density (superior ionization rate), due to larger emission of secondary electrons from the electrodes.

Another very important characteristic of the plasma produced by ABiPPS is the stability of the electric discharge through the gas with no arcing during the process. The arcs are completely suppressed due to the periodic polarity inversion.

VI. CONCLUSION

This paper proposed an asymmetric pulsed bipolar source for plasma generation, built with cascaded half-bridge submodules to form power legs. Also, a new modulation scheme was proposed with adjustable delay among the submodules aiming to reduce the width of the positive short pulses, obtaining pulses in the order of nanoseconds.

A design methodology was presented based on a mathematical analysis and a complete prototype was designed and built, based in the process requirements. The prototype was tested, and the results confirmed the desired characteristics as: flexibility to generation of short positive pulses and large negative pulses, frequency and duty cycle with independent adjustment, positive and negative pulse amplitudes with independent adjustment, and easy configuration interface by use of a soft panel.

The plasma produced through ABiPPS is totally free of arcing due to the quick periodic polarity inversion. It is possible to control the plasma density through different variables: pulse rate, positive pulse intensity, intensity of negative pulses, ratio between positive and negative periods, and rest time between the pulses. The short positive voltage pulses produce quick electronic bombardment on the electrode and increases the emission of secondary electrons from that surface. The noticeable result of this process is the far high current observed in plasma supplied by ABiPPS. High-density plasma provides opportunity to new and superior applications in different fields as sputtering film deposition, surface treatment, and chemical plasma.

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