A VERSATILE PLASMA GENERATION POWER SUPPLY FEATURING A MULTI-LEVEL CONVERTER FOR ARBITRARY WAVEFORMS GENERATION

ABSTRACT.

Purpose. Plasma technology has become of great interest in a wide variety of industrial and domestic applications. Moreover, the application of plasma in the domestic field has increased in recent years due to its applications to surface treatment and disinfection. In this context, there is a significant need for versatile power generators able to generate a wide range of output voltage/current ranging from dc to tens of kHz in the range of kVs.

Methodology. This paper proposes a versatile multilevel topology able to generate versatile output waveforms. The followed methodology includes simulation of the proposed architecture, design of the power electronics, control and magnetic elements, and test laboratory tests after building an 8-level prototype.

Findings. The proposed converter has been designed and tested using an experimental prototype. The designed generator is able to operate at 10 kVpp output voltage and 10 kHz, proving the feasibility of the proposed approach.

Originality. The proposed converter enables versatile waveform generation, enabling advanced studies in plasma generation. Unlike previous proposals, the proposed converter features bidirectional operation, allowing to test complex reactive loads. Besides, complex waveforms can be generated, allowing testing complex patterns for optimized cold-plasma generation methods. Besides, unlike transformer- or resonant-network-based approaches, the proposed generator features very low output impedance regardless the operating point, exhibiting improved and reliable performance for different operating conditions.

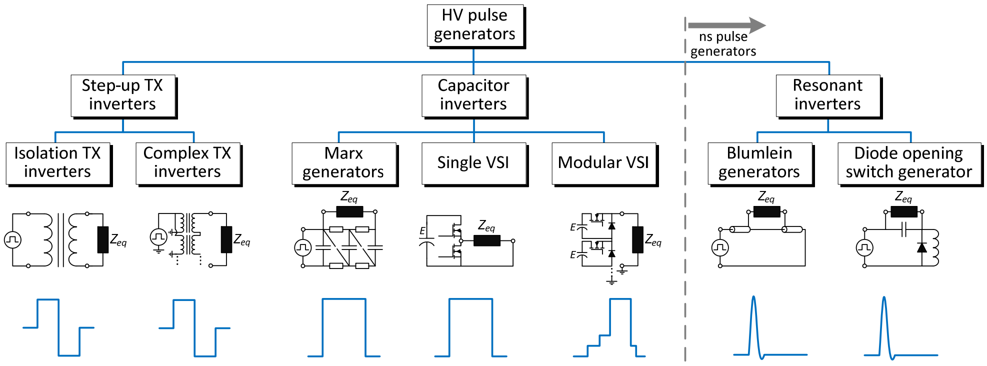
KEYWORDS.

Power electronics, cold plasma, multi-level inverter, versatile waveform generator.

INTRODUCTION

Plasmas are most commonly described as the fourth state of matter, in conjunction with gases, liquids and solids. Despite the controversy in this definition, plasma can actually show characteristic of these three matter states depending on its conditions. Its special characteristics has made plasma species interesting for many industrial, biomedical and domestic applications (Chizoba Ekezie et al., 2017, Stoffels et al., 2008, Desideri et al., 2005). As a consequence, plasma generators are of great interest nowadays. Cold atmospheric pressure plasma can deliver high concentration various reactive agents to objects to be treated, have attracted more and more attentions in the past two decades because of several emerging applications, such as material processing and plasma medicine (Jin et al., 2023, Hnatiuc et al., 2012).

Plasma systems rely on high voltage power supplies in order to generate plasma with different electrode configurations (Balcerak et al., 2013). Fig. 1 shows a summary of high voltage generators including transformer-based, capacitor-based, and resonant inverter (Lucía et al., 2019). Each of them have different features in terms of isolation, amplitude, waveform/pulse generation and waveform shape generation capabilities.



		Isolation TX inverters	Complex TX inverters	Marx generators	Single VSI	Modular VSI	Blumlein generators	Diode opening switch generator
Isolation		Yes	Yes	No	No	No	No	No
Amplitude	Pulse	Yes	Yes	No	Yes	Yes	No	No
Bipolar	Pulse	Yes	Yes	No	No	No	No	No
Width	Pulse	Y/N	Y/N	No	Yes	Y/N	No	No
Arbitrary	Pulse	No	No	No	No	Yes	No	No
Output Z	Pulse	M	M	L-M	L	L/H	H	H
Modularity		No	Yes	Yes	No	Yes	No	No

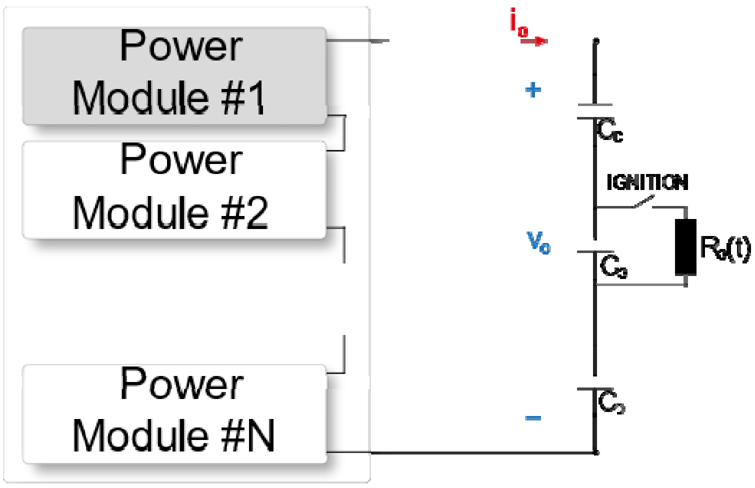
Figure 1. High voltage pulse generators (Lucía et al., 2019).

Whereas classical approaches use transformers (Fujita et al., 1999), modern power supplies use fully solid-state power electronic topologies (Millner, 2008) to provide a wide range of voltage/frequency outputs. In the past, to provide flexible solutions, power supplies with flexible pattern generation (Bae et al., 2010) or versatile generators with arbitrary waveform generation capability (Dragonas et al., 2015) have been designed. However, there is still need for more flexible generators that enable optimization of plasma generation processes and the development of new applications (Laroussi, 2009, Laroussi, 2002, Vidmar, 1990). To overcome the limitations of existing generators, in this paper a versatile bidirectional multi-level generator will be proposed that will enable to generate high-frequency high-voltage excitation while allowing flexible waveform generation and exhibiting very low output impedance, making it a perfect tool for complex processing and research purposes. Compared with (Sarnago et al., 2020), the generator proposed in this paper uses an optimized architecture that uses a single primary power board to power all the isolated output modules, and it is designed to operate in continuous operation rather than pulsed operation. As a consequence, its optimized topology and power devices enables five times the output voltage, i.e. up to 10 kV pp, and 1.2 kW under continuous operation, which is a substantial benefit for cold plasma applications.

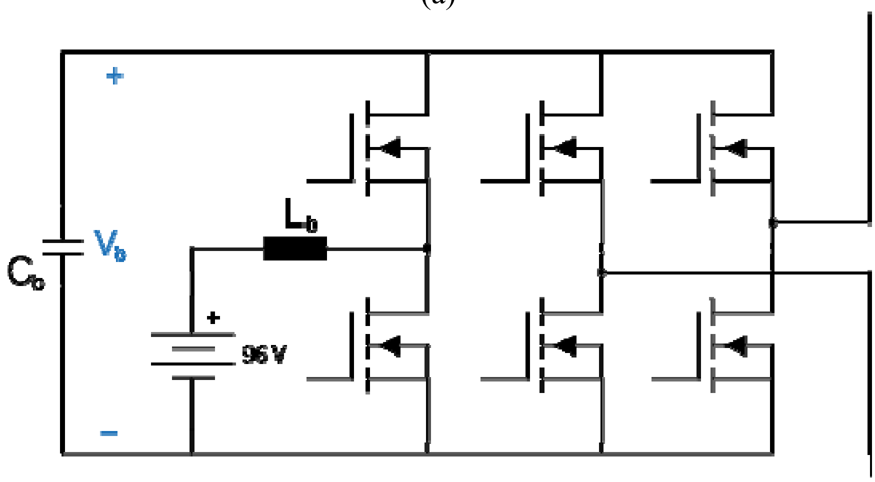
Multi-level converters present significant advantages compared with conventional and very well-known two-level converters (Franquelo et al., 2008, Younis and Mattavelli, 2023). These advantages are fundamentally focused on improvements in the output signal quality and a nominal power increase in the converter. For this reason, multi-level converters have greatly evolved in the last decades to be applied to a wide range of industrial and electrical grid applications (Harbi et al., 2023, Kouro et al., 2010), since they are considered today as a very attractive solution for medium-voltage high-power applications (Shahane et al., 2022). Multilevel converters usually use a common dc-link structure and balancing is ensured using clamping or flying capacitor techniques (Harbi et al., 2023). Space vector modulation is often used to obtain the desired output voltage while ensuring proper voltage balance (Debnath et al., 2015). In this paper, a modular isolated independent-dc-link structure is proposed to enable highly versatile operation through digital pulse width modulation individual control of each module. The proposed converter enables to generate a wide range of waveforms at different amplitudes and switching frequencies, enabling complex processing and research in plasma applications.

PROPOSED DEVICE

In order to overcome the previously described limitation of current technology, a versatile bidirectional multilevel generator (Sarnago et al., 2020, Zhu and Hu, 2013, Blinov et al., 2012) is proposed (Fig. 2(a)). This topology enables generating the required waveforms with great flexibility from dc to high-frequency ac, being able to operate with reactive loads (Alvarez-Gariburo et al., 2023). Fig 2 (b) shows the detailed implementation of each one of the power modules of the multi-level structure. It is worth mentioning that this structure is implemented using three half-bridge branches, so standard power modules can be used for its implementation.



(a)



(b)

Figure 2. Proposed versatile plasma generator: (a) architecture and (b) power module detailed implementation.

Fig. 3 shows the main simulation waveforms of the proposed structure. As it is shown in this figure, the output of each power module combines to form the total output voltage. This makes possible to obtain the high output voltages required for plasma generation in different applications. Moreover, by controlling the bus voltage of each power module and/or the number of active levels, the applied output power can be easily controlled. Unlike conventional proposals, the proposed generator allows to generate not only sinusoidal waveforms, but any arbitrary waveform required for different plasma generation processes or for easy adaptation to different temperature/density/generation process status. In the simulation example in Fig. 2, 8 power module levels are considered operating with 850 V bus voltage and 250 kHz switching frequency.

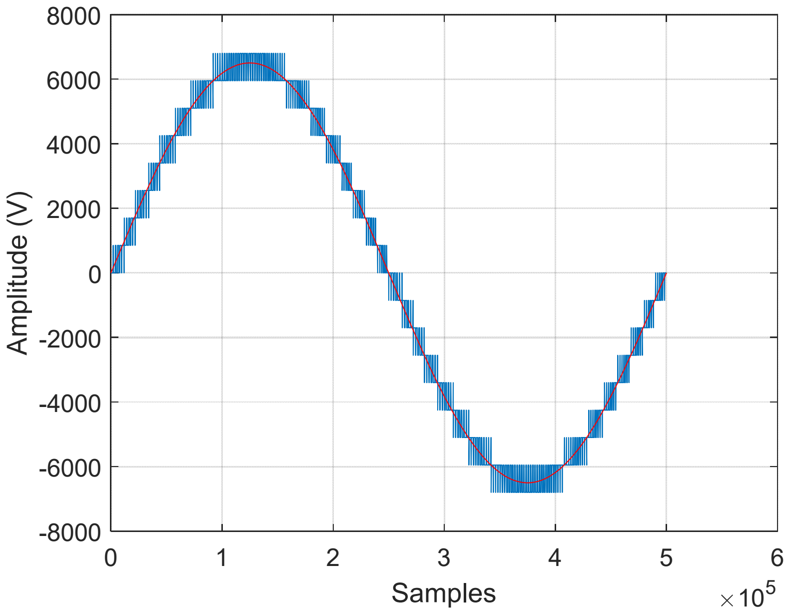


Figure 3. Main simulation waveforms assuming 250 kHz switching frequency, 8 levels and 850 V per level.

EXPERIMENTAL VERIFICATION

The proposed topology has been implemented in an experimental prototype to test the performance of the proposed converter. Fig. 4 shows a detail of the block diagram of the proposed converter, which includes a front-end ad-dc power supply, a control board with safety relay, an isolated power board to power the output modules, and a set of output modules. For safety reasons, a relay plus a series resistor is placed at the output. Table I summarizes the main specifications of the proposed converter.

Fig 5 shows a render of the designed and implemented prototype. Fig. 5 (a) shows a detail of a single power module. The proposed converter has been implemented in a modular way, so the maximum output voltage can be easily reconfigured or any power module can be easily replaced in case that accidental damage occurs. Fig. 5 (b) shows the complete prototype, including the 8 power modules, the general bus voltage and control board and a frontal user interface. The proposed converter includes USB communication and an emergency button to stop the generator operation if required.

Table I. Proposed converter specifications

Parameter	Value
Voltage	0 up to 10 kVpp (AC + DC)
Frequency	DC up to 10 kHz
Number of levels	8
Output voltage per level	800 V
Maximum power	1200 W
Control	Xilinx FPGA + optic isolated comms

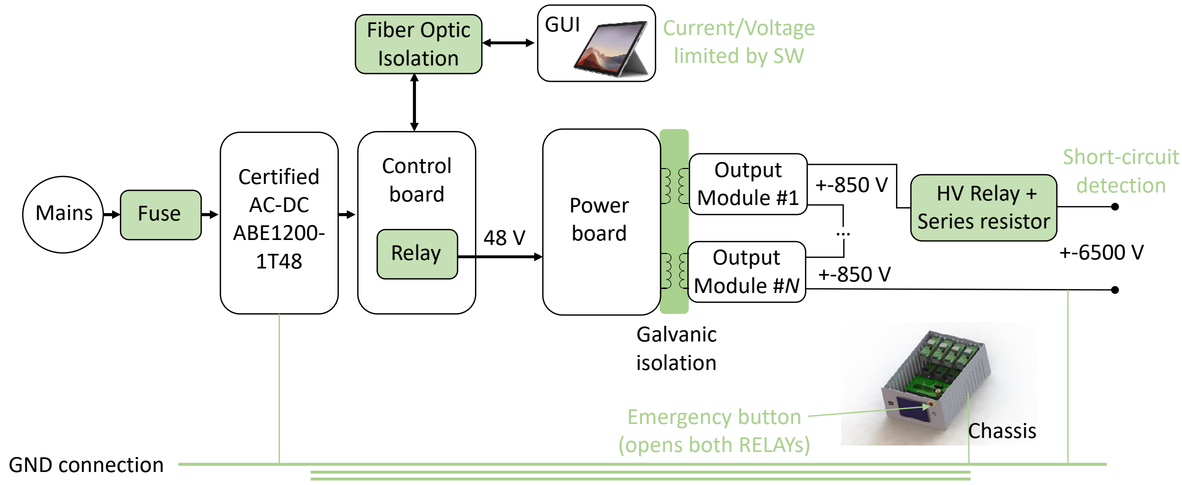
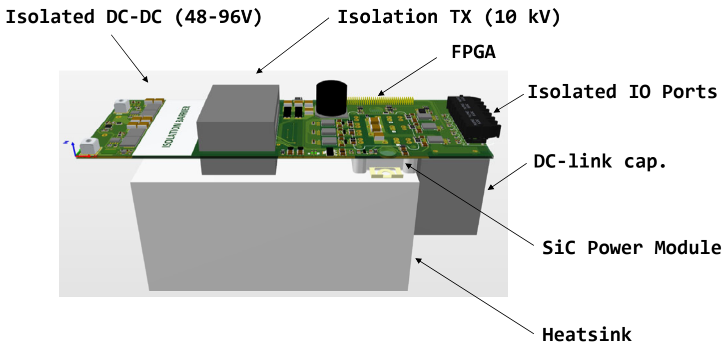


Fig. 4. Block diagram of the proposed versatile plasma generator.



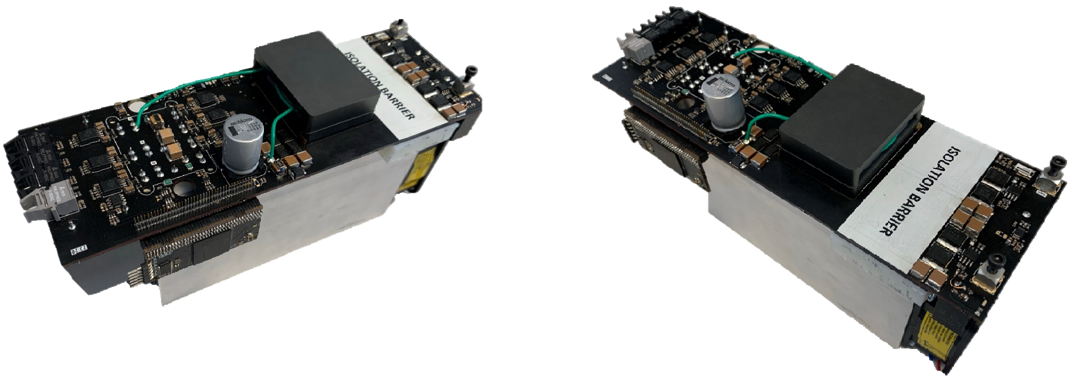
(a)

(b)

Figure 5. Experimental prototype 3D render: (a) single power module and (b) complete

plasma generation system.

Fig. 6 shows the implemented prototype. Fig. 6 (a) shows a detail of the modular power modules. These are implemented using 1200 V power devices, allowing a maximum of 800 V bus voltage per level. Besides, the PCB includes the isolation transformer using an embedded implementation, optic fibers for communications and appropriate thermal management. The complete system is shown in Fig. 6 (b), where the complete arrangement is shown during tests.



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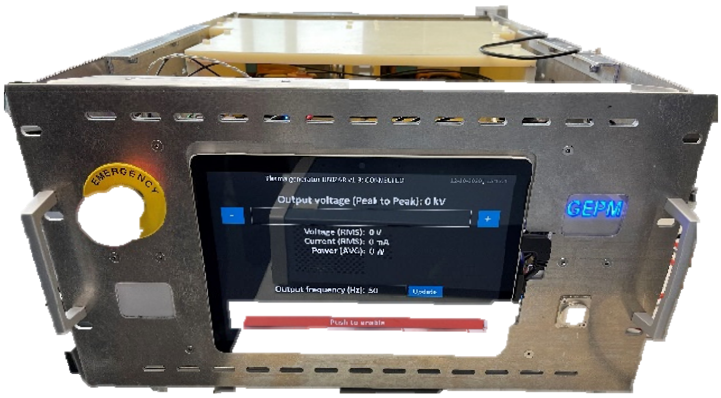

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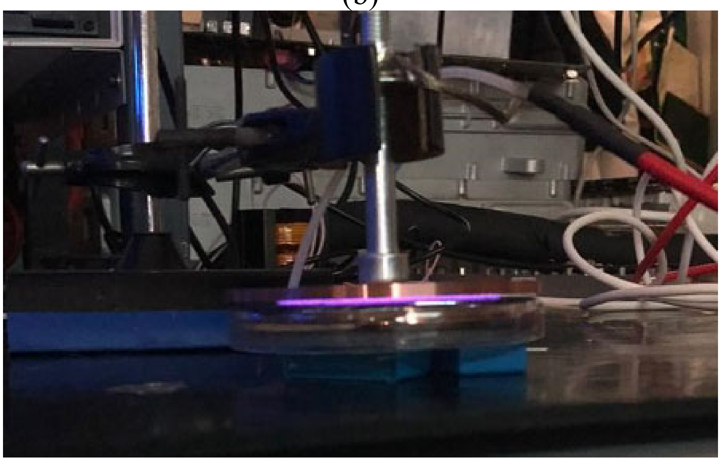
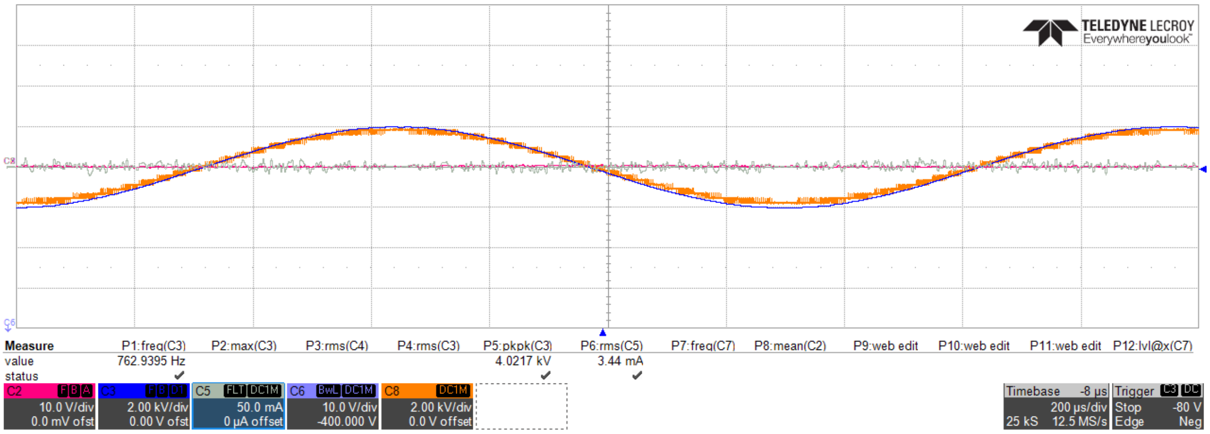


(c)

Figure 6. Experimental prototype: (a) individual power modules, (b) complete experimental setup, and (c) parallel-plate electrodes during plasma generation experiment.

Finally, the following figures shows the main experimental waveforms obtained with the proposed plasma generator at different operating conditions. The generator has been tested at a wide range of frequencies and output voltages. These testes includes both 4 kVpp and 8 kVpp operation at 760 Hz (Fig. 7), 1.5 kHz (Fig. 8), 5.3 kHz (Fig. 9) and 10 kHz (Fig. 10). The converter operates a 9 kVpp output voltage and 10 kHz. These waveforms include the output voltage and current, and shows the proper converter operation, proving the feasibility of the proposed versatile power converter.



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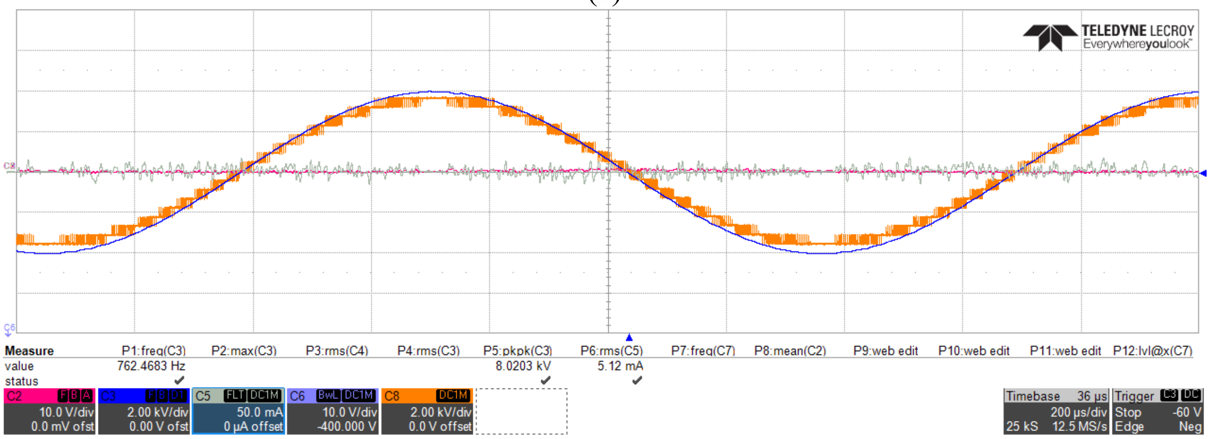

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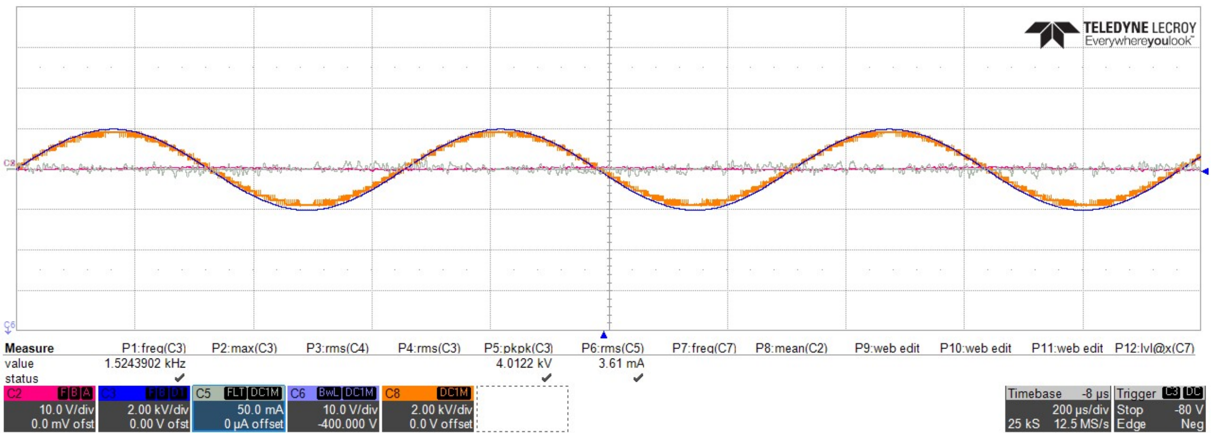
Figure 7. Main experimental results operating at 4 kVpp and 8 kVpp at 760 Hz.



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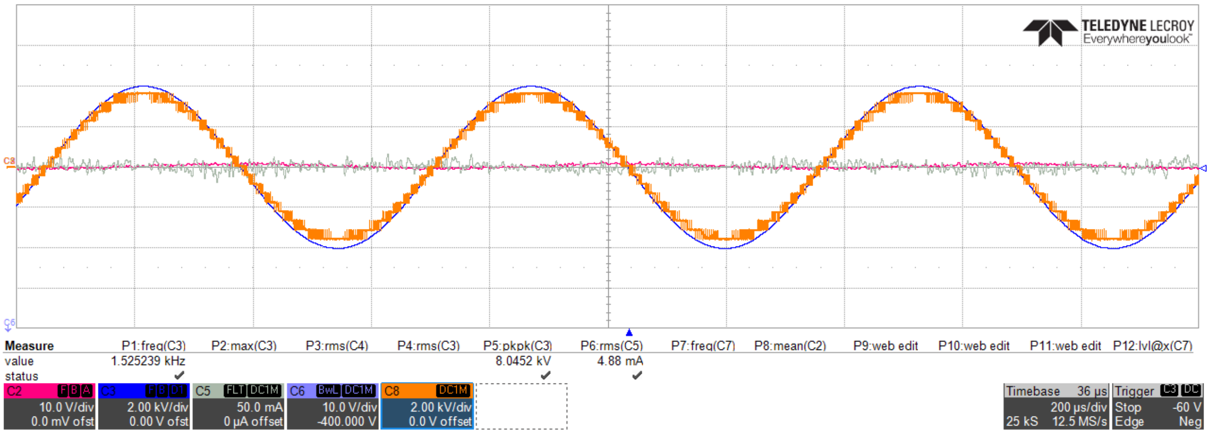
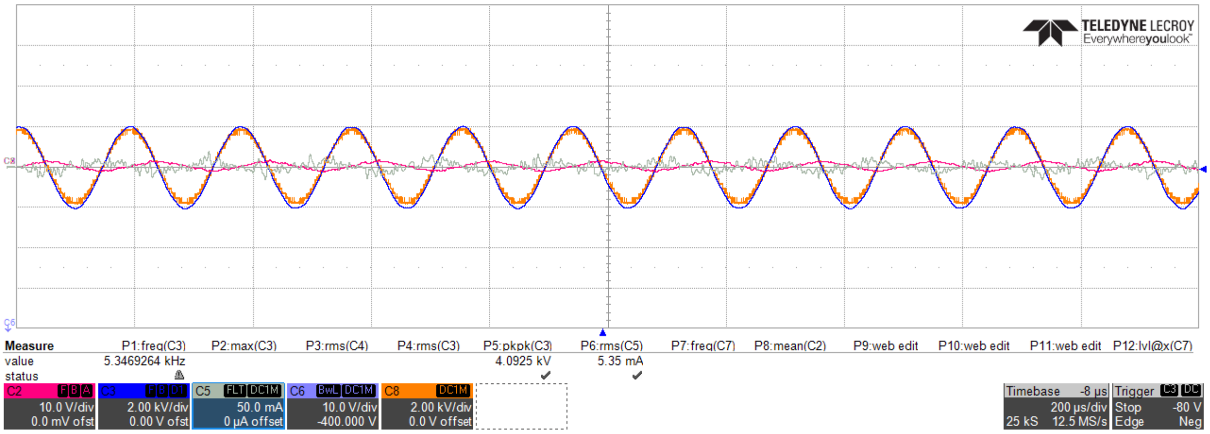


(b)

Figure 8. Main experimental results operating at 4 kVpp and 8 kVpp at 1.5 kHz.



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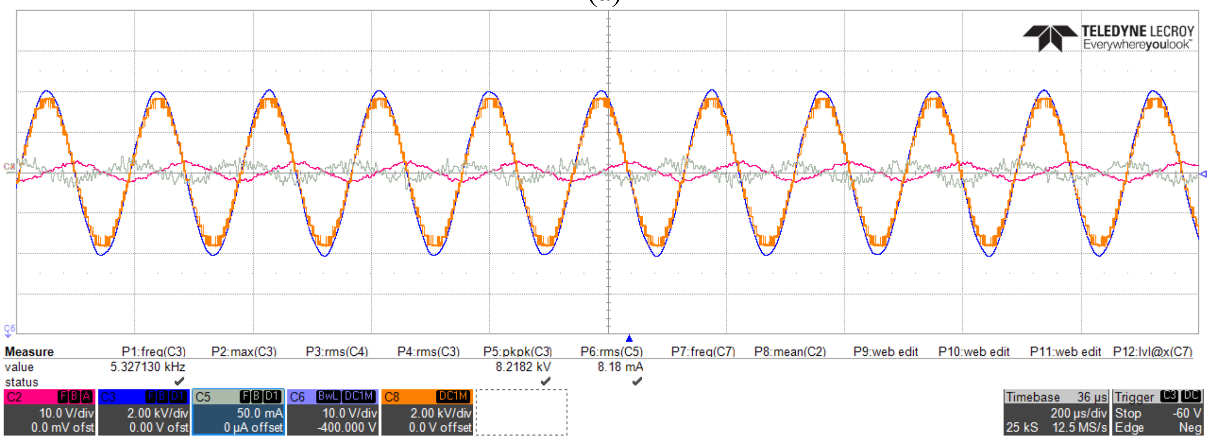

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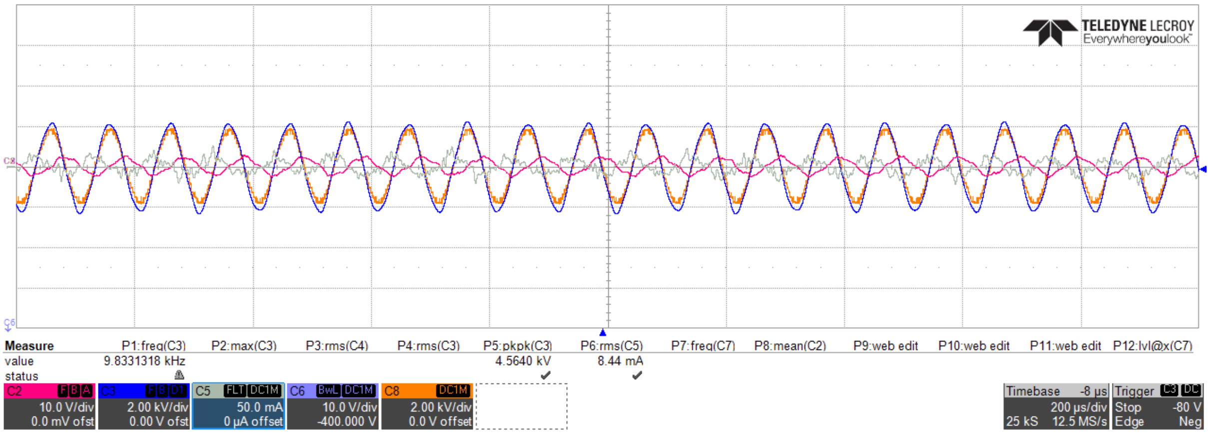
Figure 9. Main experimental results operating at 4 kVpp and 8 kVpp at 5.3 kHz.



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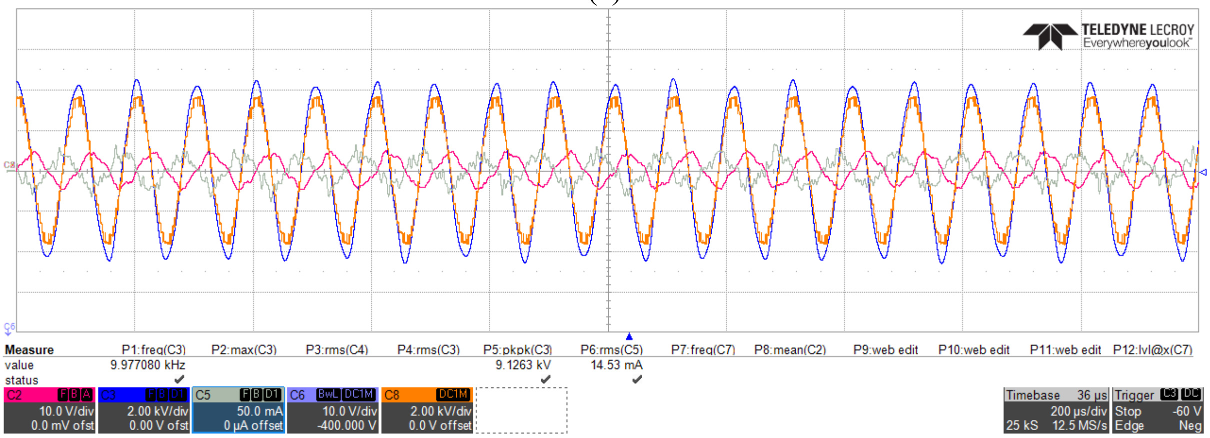

(b)

Figure 10. Main experimental results operating at 4.5 kVpp and 9 kVpp at 10 kHz.

DISCUSSION

Current state-of-the-art plasma generators commonly use transformer-based or resonant topologies that allows for an efficient and cost-effective implementation. However, these topologies require fine tuning and suffer from serious limitations when working under variable loads or operating conditions. In this context, the main benefit of the proposed generator is its versatile operation nature, allowing it to operate under a wide range of operating conditions. Unlike previous proposals, isolated buses and low output impedance allows for a precise control of the output voltage. Moreover, since a voltage-source inverter is used, instead of resonant networks, the output frequency can be accurately controlled through pulse width modulation with no penalty on performance or efficiency. Besides, its bidirectional operation allows to cope with load transients that may otherwise damage the converter. These characteristics makes the proposed converter an innovative tool specially suited for complex plasma processes or research purposes due to its improved performance and versatility. Future developments will include the use of advanced wide bandgap devices that will enable to further increase the maximum frequency and voltage operation, enabling the use of larger plasma generation electrodes.

CONCLUSIONS

Plasma technology has become essential in many industrial, biomedical and domestic applications. In this paper, a versatile generator for plasma generation has been proposed. Unlike current state-of-the-art generators, the proposed system is composed of a multi-level converter that enables the generation of high-voltage with high bandwidth and arbitrary waveform generation capabilities. The proposed converter has been designed and implemented. Experimental measurements confirm the expected operation and validates the feasibility of the proposed topology for plasma generation applications.

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