Solid-State Generation of High-Frequency Burst of Bipolar Pulses for Medical Applications

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***Abstract*— This paper describes the operation of a solid-state generator proposed to produce high-frequency bipolar high-voltage pulse bursts on resistive-type loads, intended for medical applications. The generator design is based on two independent solid-state unipolar positive Marx generators positioned back to back, where the load is placed between the outputs of the two generators. SiC metal–oxide–semiconductor field-effect transistors (MOSFETs) are used in order to allow high-frequency operation. A generator with two five-stage Marx generators is experimentally tested in order to deliver up to 5000-V/50-A bipolar pulses, with 500-ns–10-μs pulse widths and 200-ns–10-μs relaxation time between positive and negative pulses. The generator operates in the burst mode from 1 to 200 pulses, in excess of 500 kHz within the burst, which can have a repetition frequency up to 1 kHz limited by the input 1000-V/200-W power supply, with forced air cooling. Results, with resistive-type loads, for several single pulse and burst mode operations are presented and discussed.**

***Index Terms*— Biomedical applications, bipolar solid-state Marx generator, high-frequency bipolar burst, power metal–oxide–semiconductor field-effect transistors (MOSFETs), pulse power systems.**

I. Introduction

HIGH-FREQUENCY burst of bipolar microsecond-range high-voltage pulses has been recently explored to be an effective new technique associated with the traditional irreversible electroporation therapy, which mitigates muscle contraction, for example, in the nonthermal ablation of tumors [1]–[4].

Compared with a typical unipolar pulse, shown in Fig. 1(a), 2 to 400 bipolar pulse bursts, of 0.5–2.0-μs width (i.e., t_{on+} and t_{on-}, respectively, for positive and negative pulses), and several kilovolt amplitudes can be used, as shown in Fig. 1(b), with a relaxation time, t_r, up to 5 μs. These pulses can be applied during, t_{on}, up to 100 μs, with a burst frequency, $1/T_b$, of several hundreds of kilohertz, and a time between burst, $T - t_{on}$, in the range of 1 s [1]–[4].

Manuscript received February 19, 2019; revised April 5, 2019 and May 16, 2019; accepted June 14, 2019. Date of publication July 1, 2019; date of current version August 9, 2019. This work was supported by the Foundation for Science and Technology (FCT) through Project PEFPlateletValue under Grant PTDC/BTM-ORG/32187/2017. The review of this paper was arranged by Senior Editor R. P. Joshi. *(Corresponding author: L. M. Redondo.)*

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Digital Object Identifier 10.1109/TPS.2019.2923570

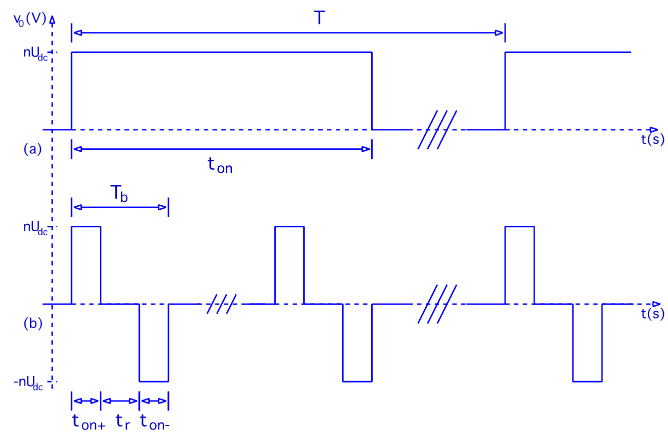


Fig. 1. (a) Traditional unipolar pulse. (b) High-frequency bipolar burst shape [1]–[4], over a resistive load, which is the typical load behavior for the biomedical applications studied.

In order to adjust the required effect on the biological cells, all these parameters need to be flexibly modified on the pulse generator. Currently, two methods are reported to generate this type of pulses: first, the use of a Marx-type generator with two different polarity input power supplies, where a number of fast solid-state switches are used to connect the main capacitors in series with different polarities, so that a positive or negative polarity pulse will be delivered to the load [5]. Second, a solid-state switch generator with two commercial switches and two different polarity input power supplies [6].

In general, microsecond-range bipolar high-voltage pulses, using semiconductor switches, can be produced by several techniques. Possibly, the most practical way is to connect an H-bridge converter to a transformer [7]. However, the use of a transformer brings various constraints and limits pulse flexibility. Alternatively, various H-bridge circuits can be stacked in order to get a high amplitude voltage, but the stage capacitors must be charge independently, typically by using transformers, which can be cumbersome and expensive [8].

Marx-type generators are also often used for producing bipolar high-voltage pulses, from pure Marx circuits [9], or in combination with the transformer [10] and with H-bridges [11]. Similarly, multilevel-type generators can be used to produce bipolar pulses [12]. However, the number of semiconductors used per stage in these circuits makes them complex to trigger, considering hundreds of kilohertz needed for these types of applications, which, in turn, affect the circuit reliability.

For simplicity and performance, one can use two positive Marx circuits connected back- to- back, using the same

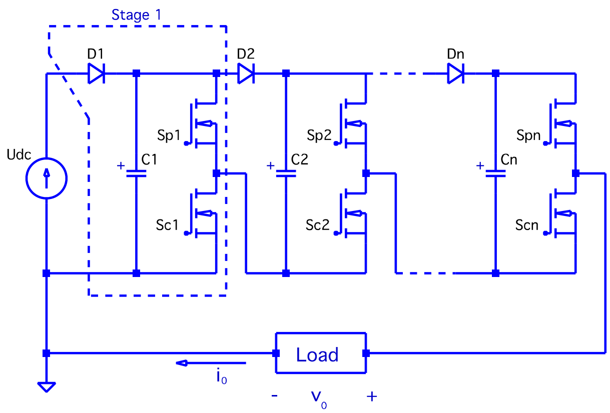


Fig. 2. Positive solid-state-based Marx generator [14].

U_{dc} power supply to charge both Marx generators and placing the load between the output of the two, as shown in Fig. 3. Although this concept has been shown for spark-gap Marx circuits [13], it has never been used with solid-state based Marx generators and for high-frequency burst applications.

Therefore, this paper presents the design and experimental results of a solid-state bipolar Marx generator developed for biomedical applications, based on the connection of two positive Marx generators back to back, producing up to 5-kV bipolar high-voltage pulses, with waveform characteristics similar to the one shown in Fig. 1, for currents up to 50 A and a frequency in excess of 500 KHz during a burst.

II. Marx Generator Topology

A. Positive Marx Generator

The bipolar solid-state Marx generator is based on the unipolar positive Marx shown in Fig. 2, with n stages, and each stage comprising a diode, D_i, an energy-storing capacitor, C_i and two switches, S_{ci} and S_{pi}, in this case, metal–oxide–semiconductor field-effect transistors (MOSFETs), for $i \in \{1, \ldots, n\}$ [14].

This circuit is designed with half-bridge switch structures, where the bottom switches, S_{ci}, are used to charge the n energy-storing capacitors, C_i, in parallel, from the dc power supply U_{dc}, and the top switches, S_{pi}, are used to connect these capacitors in series with the load R_0, applying a pulse voltage with an amplitude approximately of $v_0 = nU_{dc}$, as shown in Fig. 3, considering no voltage losses.

Fig. 1(a) shows the theoretical voltage v_0 applied to the load, normally of resistive type for biomedical applications, so that the load current follows as v_0/R_0.

B. Bipolar Marx Generator

Taking into consideration the circuit presented in Fig. 2, it is possible to connect two of these identical circuits back to back, named Generator A and Generator B, respectively, with the load placed between the two outputs, as shown in Fig. 3, each Marx with an input of U_{dc}, where the two output terminals are connected to the ground alternately.

The operation of the circuit shown in Fig. 3 can be understood by considering three operating modes. In the first mode (see Fig. 4), switches S_{ci} and S_{pi} of Generators A and B are,

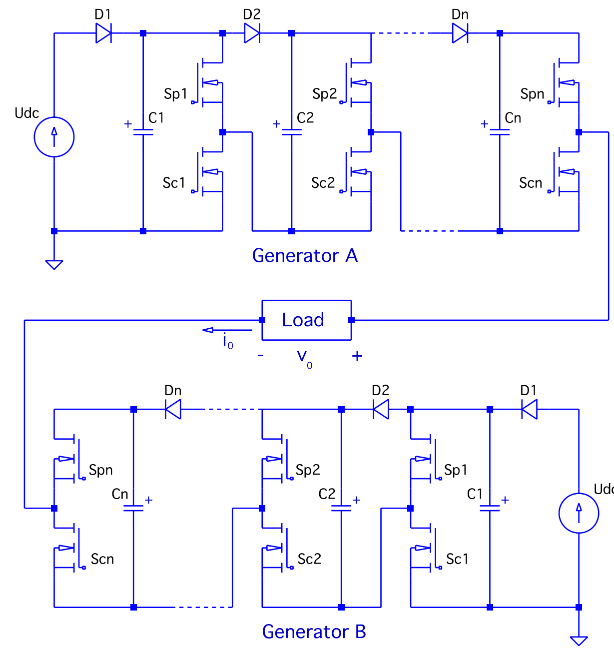


Fig. 3. Proposed bipolar solid-state-based Marx generator circuit.

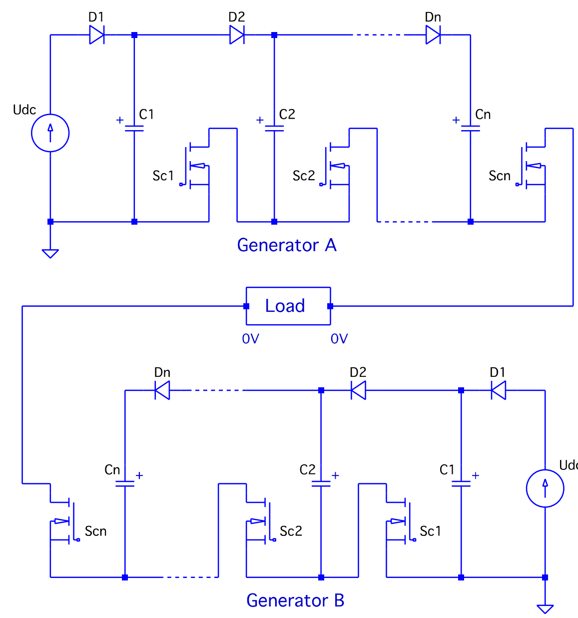


Fig. 4. Charging mode for the circuit shown in Fig. 3.

respectively, on and off. During the charging period, capacitors C_i of the two generators are charged from the dc power supply U_{dc}. The S_{ci} switches, of the two generators, guarantee that the voltage applied to the load is, approximately, zero, as shown in Fig. 1(b).

During the pulses, the power supply, U_{dc}, is inhibited, not to interfere with the charging process. This happens, also, during the relaxation time, t_r, between positive and negative pulses, as there is no time for charging. Also, during the burst operation mode, the power supply, U_{dc}, is inhibited, and there is no charging process from U_{dc}, only between bursts. Nonetheless, the S_{ci} switches continue to be set on and off, as shown in Figs. 5 and 6, to create the positive, zero, and negative states on the load.

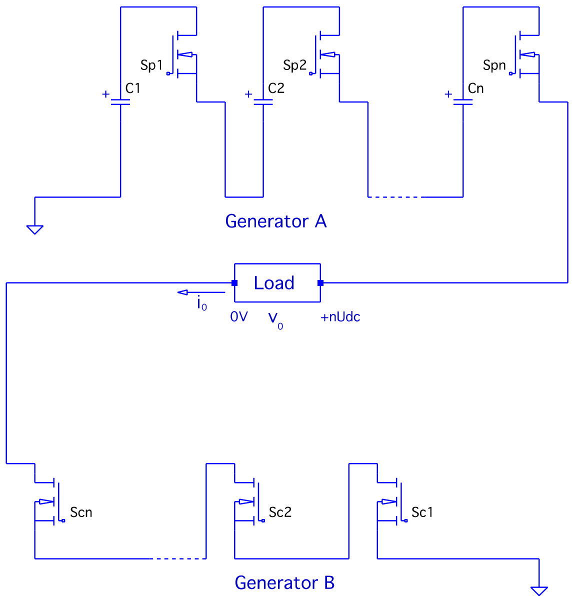


Fig. 5. Positive pulse mode for the circuit shown in Fig. 3.

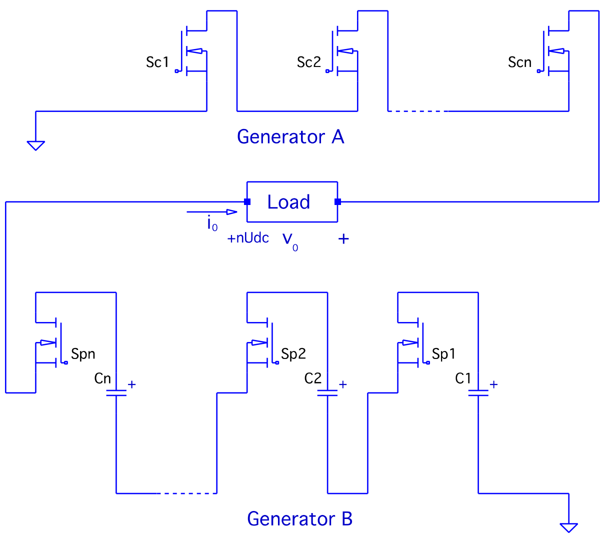


Fig. 6. Negative pulse mode for the circuit shown in Fig. 3.

In the second mode, the positive pulse (see Fig. 5), switches S_{pi} and S_{ci} on Generator A are, respectively, on and off, and switches S_{pi} and S_{ci} on Generator B are, respectively, off and on. During this period, a positive voltage pulse is applied to the load with amplitude $+nU_{dc}$, as shown in Fig. 1(b), considering the direction of the voltage drawn in Fig. 3.

In the third mode, the negative pulse (see Fig. 6), switches S_{pi} and S_{ci} on Generator A are, respectively, off and on, and switches S_{pi} and S_{ci} on Generator B are, respectively, on and off. During this period, a negative voltage pulse is applied to the load with amplitude $-nU_{dc}$, as shown in Fig. 1(b), considering the direction of the voltage drawn in Fig. 3.

III. Results and Analysis

The bipolar generator circuit shown in Fig. 3 was assembled with five stages, in each Marx generator, and a U_{dc} up to 1000 V. In each Marx generator, TO-247-3 C2M0160120D

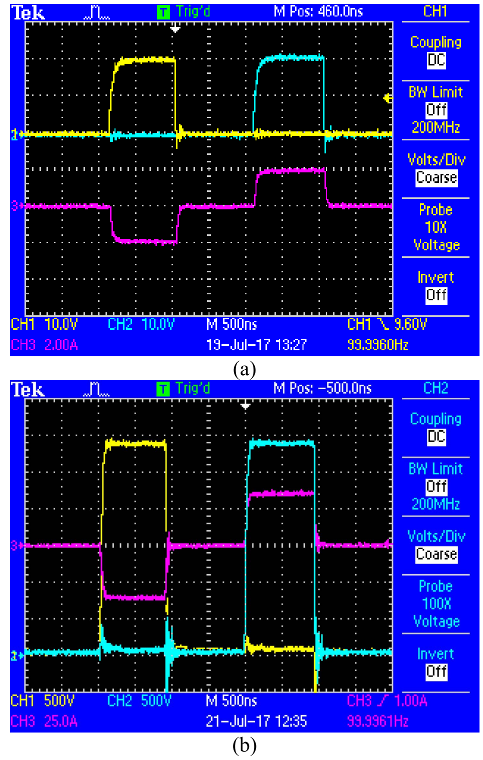


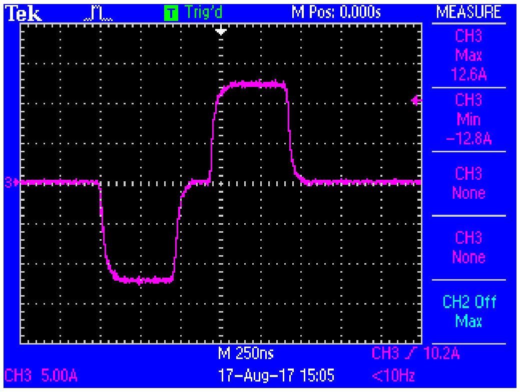
Fig. 7. (a) Top: gate signal for MOSFETs S_{pi} in generator A (yellow) and B (cyan) in Fig. 3, 10V/div. Top: load current (lilac)—2 A/div. (b) Bottom: output voltages from generator A (yellow) and B (cyan) in relation to the ground from the circuit in Fig. 3, 500 V/div. Middle: load current (lilac)—25 A/div, with 500 ns/div.

SiC Cree MOSFETs (i.e., 1200 V, 40-A pulsed current, and 160 mΩ) were used, and Panasonic 40-μF polypropylene capacitor PP 1.1-kV dc, giving a maximum energy per Marx at full voltage of 100 J. The main results for high-frequency bipolar burst are presented and discussed in this section, where, for all measurements, 100 Ω was used, using different applied voltages. Voltages were recorded with a Tektronix TPS2024B 200 MHz 2 GS/s oscilloscope, using PMK PHV1000 100:1 400 MHz 50 MΩ//7.5-pF high-voltage probe and Tektronix TPP0201 200-MHz 10 × 10 MΩ//12 pF low-voltage probe, unless described otherwise. The current measurements were recorded using a MAGNELAB current transformer, CT-D0.5-BNC, 48 Hz–200 MHz, 0.5 V/A.

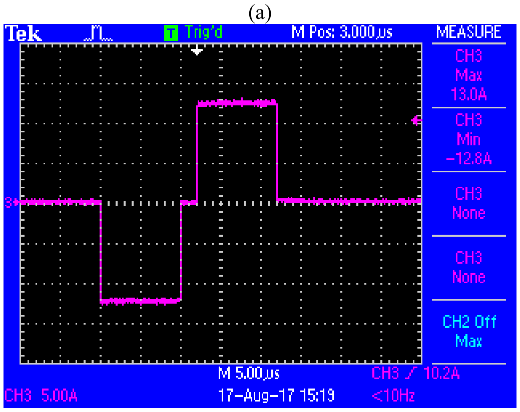
A. Single-Switch Unit Operation

Fig. 7(a) shows the S_{pi} MOSFETs gate voltages of the circuit shown in Fig. 3, from Generators A and B, with about 20-V amplitude, for near 1-μs pulsewidth bipolar pulse, and the resulting output current for 200-V pulse output. Considering the similar gate signals, Fig. 7(b) shows the voltage outputs of the two generators in relation to the ground, for about 600-V input U_{dc}, giving almost a 3000-V output 1-μs pulse voltage on the 100-Ω resistor, and the corresponding bipolar current on the load

As shown in Fig. 7, when a load is placed between the outputs of two unipolar Marx generators, the result is a bipolar signal applied to this load, if the pulse voltages from each generator are shifted from each other. In this case, there is



(a)



(b)

Fig. 8. (a) 500-ns pulsewidth on the load current $t_r = 150$ ns, 250 ns/div. (b) 10-μs pulsewidth on the load current, $t_r = 2$ μs, 5 μs/div, with 5 A/div.

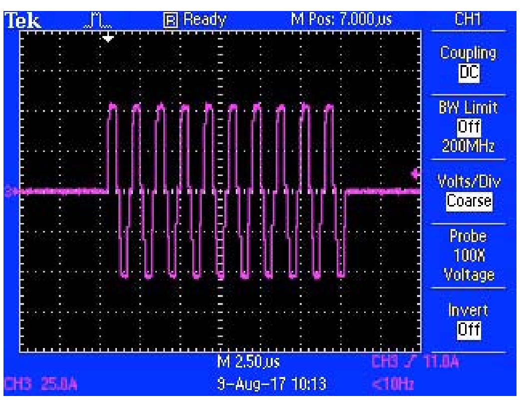


Fig. 9. Bipolar current high-frequency burst waveform, from the circuit in Fig. 3, on the 100-Ω resistive load, 25 A/div, and 2.5 μs/div.

approximately 1-μs recovery time, t_r, between the two output pulses.

Fig. 8 shows the two different pulsewidth bipolar signals on the load, with different relaxation times t_r, for 750-V pulse output.

However, the advantage of the generator shown in Fig. 3 is the ability to produce high-frequency bipolar burst, and this can be seen in Figs. 9 and 11, respectively, for two different operating conditions. In Fig. 9, one can observe the current, about 50-A amplitude, on the 100-Ω resistive load for a burst of ten bipolar pulses, with 5-kV amplitude, beginning with a positive pulse, with approximately 667-kHz frequency during the burst, for a 0.5-μs positive/negative pulsewidth. In this case, no obvious voltage drop during the pulse burst exists, as the pulse energy is much lower than the Marx stored energy.

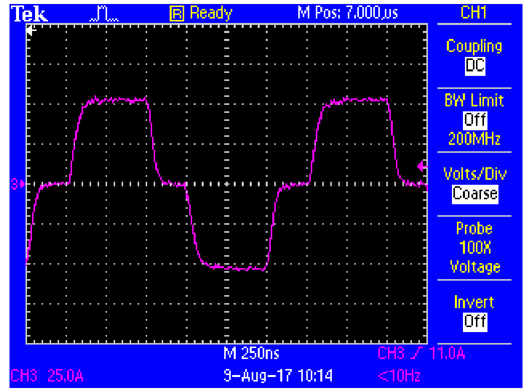


Fig. 10. Zoom-in view of the waveform in Fig. 9, 25 A/div, and 250 ns/div.

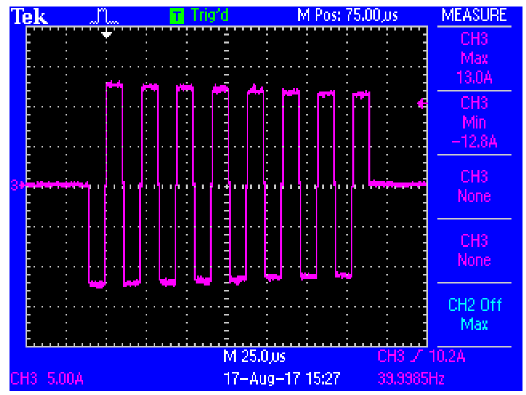


Fig. 11. Bipolar current high-frequency burst waveform, from the circuit in Fig. 3, on the 100-Ω resistive load, 5 A/div, and 25 μs/div.

Details of bipolar current high-frequency burst pulses shown in Fig. 9 can be seen in Fig. 10, where the relaxation time between positive and negative pulses is about 200 ns.

Similarly, in Fig. 11, one can observe the current, about 12-A peak, on the 100-Ω resistive load for a high-frequency burst of eight bipolar pulses, beginning with a negative pulse, with approximately 50-kHz frequency during the burst, for a 10-μs positive/negative pulsewidth, and 1200-V amplitude. In this case, it is observed a clear voltage drop on the amplitude during the pulses as the pulse energy is higher than in operating condition in Fig. 9; as explained previously, there are no capacitors charging during burst mode.

Finally, the layout of the assembled generator inside a 19” rack is shown in Fig. 12, where the main components are observed: Marx Generators A and B, 1000-V/200-W power supply, and microcontroller-based control system.

The main limiting factor for pulsewidth and relaxation time is presently the optical fiber triggering electronics (i.e., optical receiver HFBR-2521Z, optical transmitter HFBR-1521Z, and optical cable HFBR-RUS100Z) used to set on and off the MOSFETs from the control system, as there are propagation delays for turning on and off, between 100 and 200 ns. If this can be improved, lower pulse widths and propagation times

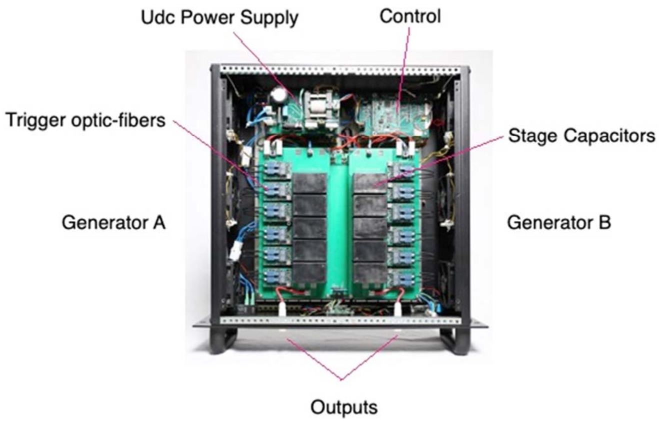


Fig. 12. Picture of four implemented Marx stages from the circuit in Fig. 2.

can be set, as the MOSFETs can be run with times in the order of dozens of nanoseconds.

IV. Conclusion

A low-complexity operation Marx-type generator was described and tested to produce bipolar high-voltage pulse bursts on resistive-type loads, intended for medical applications. The circuit consisting two autonomous unipolar solid-state Marx generators connected back to back proves to produce up to 5-kV/50-A bipolar high-voltage pulses, in the microsecond range, with a burst frequency in excess of 500 kHz, and waveform characteristic similar to the one shown in Fig. 1, which are adequate for irreversible electroporation therapy of solid tumors under nonthermal conditions.

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