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A Repetitive Bipolar Pulsed Power Generator Based on Switched-capacitor Concept

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ABSTRACT

This paper presents a pulsed-power generator that can produce a high voltage bipolar pulse from a relatively low-voltage input source, based on the switched-capacitor concept. The circuit boosts the input voltage by storing energy in several capacitors in a predefined pattern and simultaneously releasing it to the load. It is worth noting that the structure can short-circuit its output terminal while charging the capacitors without using any switches across the load. This topology is mainly suitable for applications requiring a high voltage pulse and only having access to low voltage input sources. Moreover, thee structure can generate a combination of wide and narrow pulses by alteranting its output voltage between two different values. Precise calculation and employment of capacitors ensure that the structure can properly generate the intended output pulses with an acceptable ever-so-slight voltage drop. Finally, MATLAB Simulink was used to evaluate the circuit's operation, and experimental tests were conducted on a laboratory setup, where the results confirmed the proper performance of the circuit.

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1. INTRODUCTION

High voltage pulsed power supply with repetitive rate has found widespread use in industrial, medical, and environmental applications [1]. In this regard, the following utilizations have been reported in the literature: plasma source for ion implantation, microwave generation, metal forming, water purification, food sterilization, eye surgery, cancer treatment, and reducing muscle contractions during irreversible electroporation [2-8]. Considering the vast application of these pulse generators, optimizing their circuit design is crucial. Applying the avalanche breakdown property of transistors is one of the methods to achieve an ideal design for generating pulses [9]. The other important design issue of such circuits is the switching process of the components [10]. These circuits are mainly composed of several switching states, each providing a part of the overall output voltage waveform. The switches used in these generators are of different types, such as electronic switches and fast diodes, including MOSFET, BJT, and IGBT.

Depending on the type of switches used, the structure, its control, and maintenance can be more complicated and costly. Therefore, achieving high- voltage high-energy pulses at an acceptable cost should be addressed for the aforementioned applications. Employing BJT transistors with avalanche breakdown for generating voltage pulses is one of the approaches to achieving a compact design [11]. However, the blocking voltage of semiconductor switches is one of their most significant limitations. Employing either a series connection of switches or a step-up transformer has been proposed in different configurations to overcome this issue [12]. Nevertheless, transformer losses, size, and difficulties in matching it with load impedance lead to a decline in the system's reliability and efficiency. Additionally, the probability of a switch failure in these two methods is significantly higher due to the absence of proper protection circuits.

Another method of achieving a pulsed power generator is using the Marx structure. In this structure, similar switches are used to charge capacitors in parallel and discharge them in series across the load. Marx generators (MGs) require a significantly high input voltage to merely

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produce a high voltage pulse (without any transformers). However, it obliges a specific triggering circuit to precisely control the switches. Despite sufficient rise time, this structure suffered from low efficiency and repetition rate due to the need of too many circuit elements. Additionally, short life time of the circuit was the other disadvantage the traditional Marx pulse generators. Turning to the applications that use low voltage power supplies as an input source, using Marx structure requires too many modules. This feature results in higher size, cost and control complexity of the circuit.

In recent years, MG has had dual functions by combining repetitive rate of semiconductor switches with voltage adder from Marx principle, which helps decrease the pulse's rising time compared to the conventional circuits, leading to a more precise and better-formed pulse. However, MG structures may employ many modules for applications requiring low-voltage input sources, resulting in increased control complexity and cost. Multistage and/ or modular switched-capacitor circuits (using low-voltage semiconductors) were developed to address the abovementioned limitations, besides easing the design and control process. The fundamental building block of these circuits is based on MG sub-modules, in which the majority of the circuit components can withstand a voltage similar to the input voltage [13]. A repetitive Marx-type generator based on half and full-bridge Switched-Capacitor (SC) cells is introduced by Sakamoto et al. [14], facilitating independent control of pulsed power parameters. The modularity of the generator not only has led to an easily adjustable pulse signal but also more output voltage levels for reaching higher voltages. However, it requires numerous capacitors and switches to generate the intended pulse. A cascaded H-bridge multilevel inverter for liquid food sterilization eliminating bulky transformer requirements is proposed by Jambari et al. [4]. Although this sturcutre and its performance are straighforward, it suffers from using several independent input sources. A bipolar high-frequency narrow pulse generator based on two independent solid-state unipolar positive MGs positioned back to back for medical application was suggested by Redondo et al. [15]. Notably, each side of the converter is used only in half of the time of a cycle. This feature obliges using a high number of circuit component. Despite having a simple operation control, this pulse generator implements two separate input sources for its two sides.

In general, bipolar high-voltage pulses can be generated with several techniques using semiconductor switches, of which the most common approach is to combine a unipolar pulse generator and an H-bridge on the load side [16]. Besides, using a single primary-side multiple secondary-side transformer-based topology was introduced by Lee et al. [16] in which the number of secondary windings is dependant to the multiplying ratio of the pulse generator. Although this feature helps isolating the input side from the output side, it increases the overall size, weight and cost of the converter. Additionally, the high current stress on the primary side of the transformer makes it vulnerable to failure, reducing the reliability of the circuit. Yet, the main disadvantage of this structure is a large number of H-bridge inverter switches, inflexibility of the pulse, constraints of the required modulator.

Another type of bipolar modular structure is a multistage structure in which a low voltage submodule is stacked in series to generate a high voltage. Two unipolar modulators are used to construct a bipolar pulse power modulator by Liu et al. [17]. Hence, compared to a unipolar pulse power modulator, this requires twice the number of modules to configure the same output voltage level. A multistage modulator structure using several bipolar sub-modules was proposed by Yao et al. [8] and Gholamalitabar et al. [18]. Bipolar sub-modules capable of generating both positive and negative outputs are stacked in series to generate high voltage bipolar pulses. Additionally, the number of components required to construct this complex module can be reduced. As an extension to the research presented by Gholamalitabar et al. [18], a uni/ bipolar high-voltage pulse generator based on a side bridge has been proposed. The primary advantage of this method is its ability to generate various high-voltage unipolar and bipolar pulse waveforms with a relatively low-voltage dc power supply. Using relatively low-voltage IGBT for implementing submodules of the full-bridge is the other advantage of this structure. Unlike the Marx generator that simultaneously charges the capacitors, this topology benefits from the sequential charge of the capacitors. This feature helps ensure a lower current on the IGBTs of the submodules. Furthermore, a modular controllable bipolar pulse generator based on the Capacitor Switch Voltage Multiplier (CS-VM) was introduced by Alijani et al. [19]. In this strategy, capacitors are charged with a predetermined pattern and discharged across the load in a specified sequence.

Accordingly, introducing a pulse generator circuit based on SC Voltage Multiplier (SC-VM) is presented in this study. In this method, similar to CS-VM, several capacitors are charged in predetermined time intervals while the load is short-circuited. Then, all or several of these capacitors are discharged into the load in the final stages. Consequently, a multiplied pulsed voltage is formed from a low-voltage DC source. To further discuss the proposed concept, the rest of this article is organized as follows: Section II describes the topology and its operating principles, such as charging and discharging paths and bipolar pulse generation. It also provides capacitance calculations and a brief comparison with similar works. Then, the circuit structure is evaluated through simulation and experiment where the results are added in section III. Finally, the paper is concluded in section IV.

2. PROPOSED CIRCUIT

2. 1. Principles of Operation

The fundamental idea of the proposed circuit is to charge several capacitors via the SC-VM network and then connect them in series to generate high voltage pulses at the output. The proposed structure is depicted in Figure 1. The circuit comprises six electrolyte capacitors and 23 power switches, including 13 unidirectional and five bidirectional ones. The switches S6, S9, S10, S11, and S15 are bidirectional switches that utilize the same control signal for both switches. As a result, the overall structure necessitates using only 18 driver circuits.

Three distinct patterns (P_n) for voltage multiplication are applicable to the circuit. As summarized in Table 1, each pattern charges the capacitors up to a predetermined amount that yields a specific voltage amplitude. Since the third pattern (P_3) results in the highest voltage amplitude, the rest of the paper is based on applying this pattern to the circuit. This pattern charges the circuit capacitors in a way that V_{C5} is four times the input voltage (V_{in}), which is twice the V_{C1} and four times V_{C3}. Nonetheless, as shown in Figure 2, the proposed structure is extendable to produce higher voltages where the highlighted part is repeated n-times to reach the intended voltage amplitude. In that case, the main part of the circuit operates with any of the abovementioned patterns. However, based on the application and user's preferences, the extension part can either double the capacitors' voltage in every step or charge all of them with the same voltage as C5 and C6. However, there are a few limiting factors in both approaches, such as the amplitude of input voltage and the rating of semiconductor devices in the circuit. As a result, the intended output waveform for the basic circuit of Figure 1, is achieved by using the operating sequence presented in Table 2 where the corresponding current path of each stage illustrated in Figure 3. Accordingly, all capacitors are charged during the first six stages of operation. In steps 7 and 9, negative and positive voltage pulses are generated by a specific combination of capacitors and applied to the load.

During the first (Figure 3a) and second (Figure 3b) stages of the circuit's operation, capacitors C_3 and C_4 are directly charged by the input source up to V_{in}. As shown in Figure 3c, these two capacitors are connected in series with C1 causing it to charge to a maximum of 2Vin in the third stage. Similarly, capacitor C2 undergoes the same process in the fourth stage (Figure 3d). Then, C1, C3, and C4 charge C6 up to 4Vin (Figure 3e). Likewise, capacitor

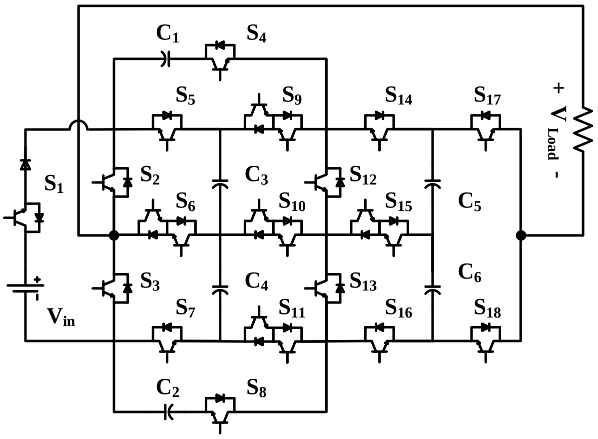


Figure 1. General structure of the proposed pulse generator

TABLE 1. Possible charging patterns

Charging Pattern	Capacitors' Voltage			Max. Output Voltage
	C_3, C_4	C_1, C_2	C_5, C_6	
P_1	V_{in}	V_{in}	V_{in}	$5V_{in}$
P_2	V_{in}	$2V_{in}$	$2V_{in}$	$8V_{in}$
P_3	V_{in}	$2V_{in}$	$4V_{in}$	$12V_{in}$

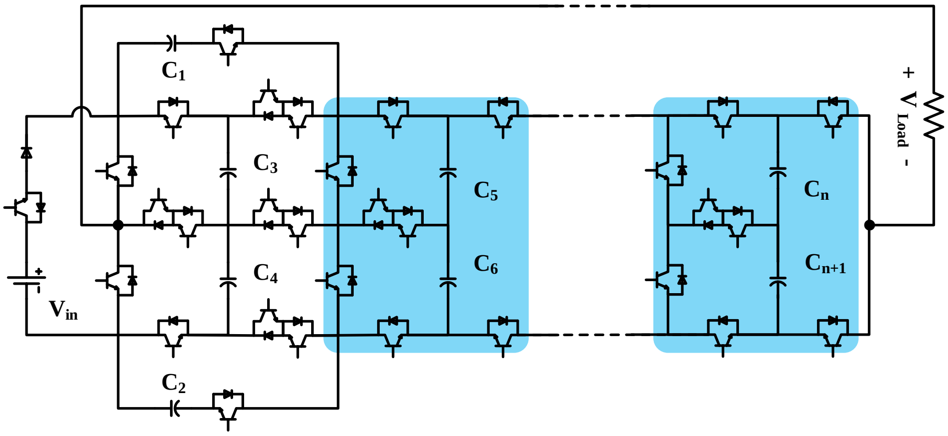
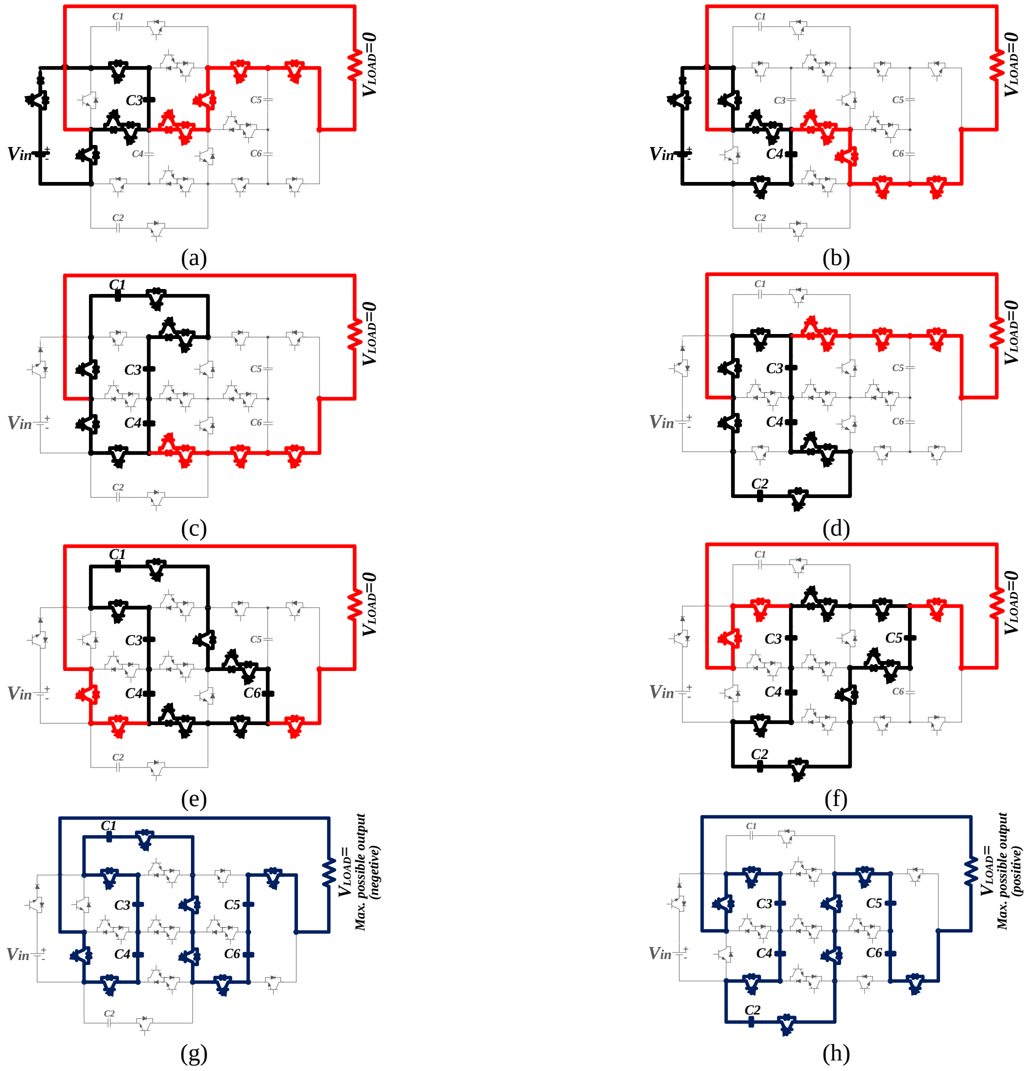


Figure 2. Extension of the presented topology

TABLE 2. Operational sequence considering pattern P3

Stage	Description	V_{out}
1	Charging C_3	0
2	Charging C_4	0
3	Charging C_1	0
4	Charging C_2	0
5	Charging C_6	0
6	Charging C_5	0
7	Discharging C_2, C_3, C_4, C_5, C_6 to the load	$-12\times V_{in}$
8	Charging C_4	0
9	Discharging C_1, C_3, C_4, C_5, C_6 to the load	$+12\times V_{in}$
10	Charging C_3	0

C5 is charged to the same voltage level in the sixth stage (Figure 3f). It is worth noting that the load is short-circuited while the capacitors are being charged, so the output voltage is kept at zero. Finally, as presented in Figure 3g, the charged capacitors C2, C5, C4, C6, and C3, are coupled in the seventh stage to generate a final voltage of -12Vin. This results in the generation of a negative voltage pulse. Again, the load is short-circuited in the eighth stage (Figure 3b). Afterwards, capacitors C1, C5, C4, C3, and C6 are discharged into the load in the ninth stage, producing a positive voltage pulse with an amplitude of 12Vin (Figure 3h). The tenth stage is a repetition of the first stage where the load voltage becomes zero (Figure 3a). For instance, switches 1, 3, 5, 6, 10, 12, 14, and 17 should be turned on to implement the first stage, and other switches should remain off. The time sequence required by all switches for one cycle of the output voltage is shown in Figure 4.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 3. Various current paths regarding ten stages of Table 2 (black=charging path of the capacitors, red=current path of the load, blue=discharging path of the capacitors to the load) (a) stages 1 and 10, (b) 2 and 8, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, and (h) 9

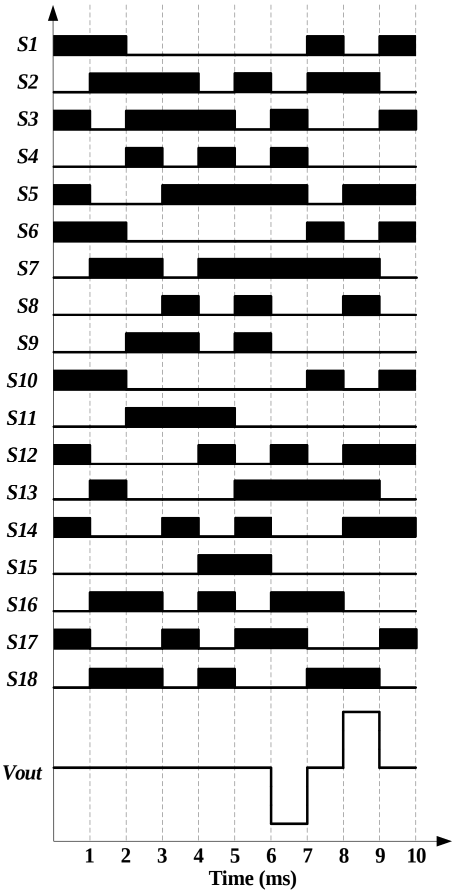


Figure 4. Time sequence of all switches and the corresponding output voltages

2. 2. Capacitance Determination

It is essential to select proper capacitances to keep their voltage drop at a specific amount during the whole pulse generation process. Considering the charging pattern of P_3, as some capacitors are charging others, they experience a k percent voltage drop (0<k<1). For instance, C1 is charged by the series connection of C3 and C4, where their total charge is shared with C1. This process consumes some energy that C3 and C4 should provide. So, a part of their voltage (or energy) is always devoted to this charge sharing and not transferred to C1. This phenomenon is modeled and presented in its voltage by parameter k. Therefore, instead of reaching 2Vin, C1 can only get to 2(1-k)Vin. Hence, based on the operational sequence of Figure 4, each capacitor's voltage equals [18]:

$$\begin{cases} V_{C3} = V_{C4} = V_{in} \\ V_{C1} = V_{C2} = 2(1-k)V_{in} \\ V_{C5} = V_{C6} = 4(1-k)^2 V_{in} \end{cases} \tag{1}$$

Hence, the amplitude of the output voltage reaches:

$$\begin{aligned} V_{out-\max} &= \left(2+2(1-k)+8(1-k)^2\right) V_{in} \\ &= 2\left(4k^2-9k+6\right) V_{in} \end{aligned} \tag{2}$$

Which, equals to $12V_{in}$ in ideal conditions (k=0). Accordingly, the required capacitances are determined:

$$C_i \geq \frac{V_{out}.\Delta t}{R.a.V_{Ci}} \qquad i=1,2,\ldots,6 \tag{3}$$

Where Δt is the total pulse width, aV_{Ci} is the voltage drop of each capacitor while discharging, and R is the load impedance. Accordingly:

$$C_{3,4} \;\square\; 2C_{1,2} \;\square\; 4C_{5,6} \tag{4}$$

Thus, each capacitance can be designed for a given voltage drop, maximum pulse width and load impedance. Figure 5 presents the changes in the circuit capacitances versus variations of these parameters.

2. 3. Comparison

Table 3 briefly compares the proposed circuit to the ones presented by Sakamoto et al. [14], Gholamalitabar et al. [18] Alijani et al. [19] and Redondo [20] ,where the maximum operating voltage in all of them is within the same range. For sake of fairness, the comparison is made among structures that benefit from a similar gain of 12, defined as the ratio of the output voltage amplitude to the input one ($V_{out-max}/V_{in}$). This factor implies that in the case of using the same input source with the same amplitude, all of these topologies produce a pulsed voltage whose amplitude is 12 times the input one. Nevertheless, the input voltage directly dictates the choice of circuit elements, especially switching devices. So, these topologies may differ in their choice of elements, but their overall performance yields the same result. Accordingly, the proposed structure necessitates fewer semiconductor devices (both power switches and diodes) to reach the same gain. Moreover, employing bidirectional switches results in requiring fewer driver circuits. It is worth mentioning

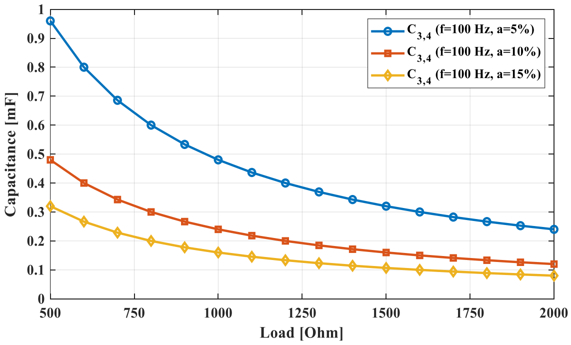


Figure 5. Variation of circuit capacitances

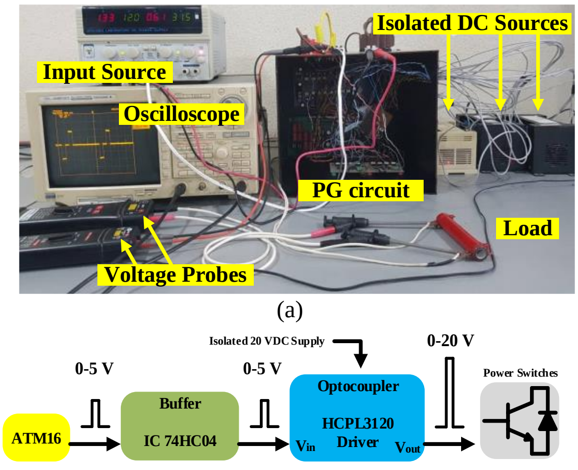
TABLE 3. Comparison of similar structures

Parameter	Proposed	[14]	[18]	[19]	[20]
Voltage Gain	12	12	12	12	12
Number of switches	23	48	23	26	44
Number of series diodes	1	12	5	6	23
Number of driver circuits	18	48	20	26	44
Number of capacitors	6	12	6	6	12

that topologies given by Sakamoto et al. [14] and Redondo [20] used twice the number of capacitors as others. It is notable that despite Sakamoto et al. [14] has a only two simple modes of operation, it requires numerous components. The topologies introduced by Gholamalitabar et al. [18] Alijani et al. [19] and Redondo [20] mainly befit from their fast boosting, and their easily expandable structures. However, they require more semiconductor devices as well as driver circuits. Afterall, the proposed structure outperforms the other similar ones in this context.

3. RESULTS

Considering the precise specifications of the switches, and capacitors based on the test conditions, the circuit was simulated in the MATLAB Simulink environment to verify the correctness of its design. Then, as shown in Figure 6a, a laboratory prototype was implemented to validate the simulation results. Moreover, Figure 6b illusterates the control diagram of the circuit switches where switching signals are provided by the microcontroller. After buffering and isolation, these signals are amplified to be applied to the switches. It is notable that both simulations and experimentations were conducted with the same properties. The parameters of the test system are listed in Table 4.



(a)

(b)

Figure 6. (a) Laboratory test setup, and (b) control diagram of the circuit switches

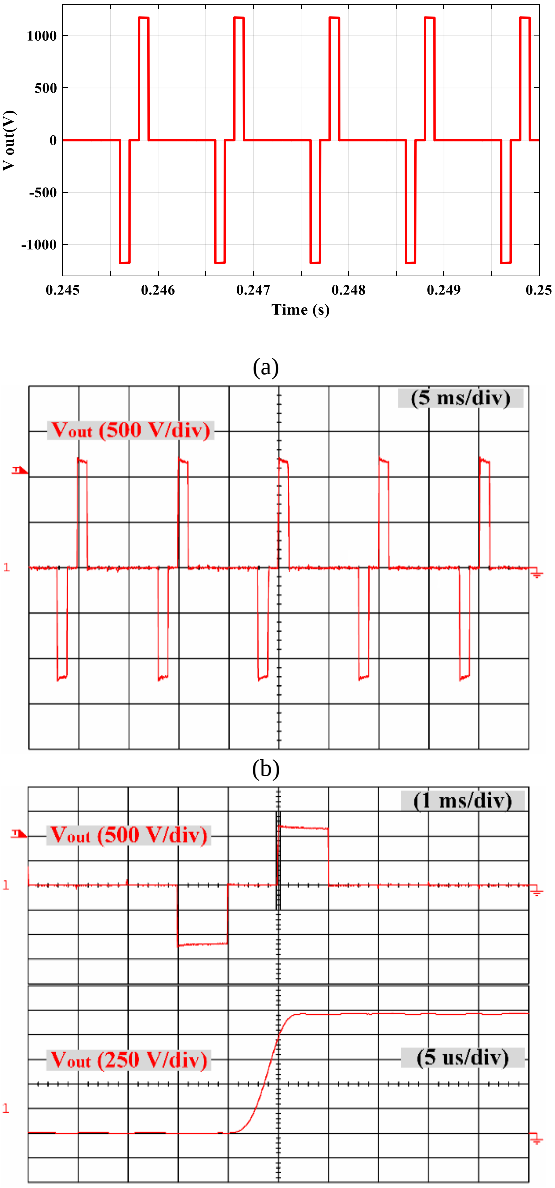
TABLE 4. Circuit parameters of the proposed structure

Parameters	Value
Input voltage	100 V
Output voltage	1200 V
Output frequency	100 Hz
Power switches	15n120
Load	1 kΩ
Capacitors	C1-C2 =240 µF, 250 V C3-C4 =500 µF, 150 V C5-C6 =120 µF, 450 V
Driver	HCPL3120
Microcontroller	AVR (ATMEGA16A)

Notabaly, the size of the circuit capacitors is determined based on the section 2.2. Then, the nearest commercially available capacitances were selected for the experiments. In such conditions, the pulse generator's output is as Figure 7, with an amplitude 12 times the of the DC input voltage. Each stage of the output voltage lasts one millisecond, resulting in a signal with a frequency of 100 Hz. Therefore, a 1.2 kV pulse is generated from a 100 V input assuring the sufficient behavior of the circuit in boosting a low voltage DC input tweleve times to generate the intended output. Furthermore, to better evaluate the speed of the pulse generation process, Figure 7c depicts a rise-time of approximately 5 microseconds. Accordingly, the voltage waveform of half of the capacitors is shown in Figure 8. Since the behavior of the circuit capacitors is similar in pairs, it is sufficient to present only half of them.

As can be seen, the desired pulse is achieved by selecting appropriate capacitors while maintaining their voltage balance. In such conditions, the voltage of the C3, C1, and C5 oscillates around 100, 200, and 400 volts, respectively. Each voltage waveform has a ripple less than 5 percent, confirming their precise design. Since the circuit can operate with various frequencies, Figure 9 provides two sample output voltages with 50 and 1000 Hz frequencies. Moreover, the proposed circuit can generate a combination of wide and narrow pulses, as some applications may require them.

For this purpose, the output voltage should alternate between two specific values at a certain rate to produce such waveforms. For instance, Figure 10 illustrates the circuit's output voltage as a combination of wide (100 Hz) and narrow (12.5 kHz) pulses in which by alternately bypassing capacitors C3 and C4, the pulse amplitude changes between 1 and 1.2 kilovolts. Afterall, the experimental results confirm the aformentioned calculation and simulations, implyng the proper performance of the proposed topology as a pulse generator suitable for applications with a single low voltage input source.

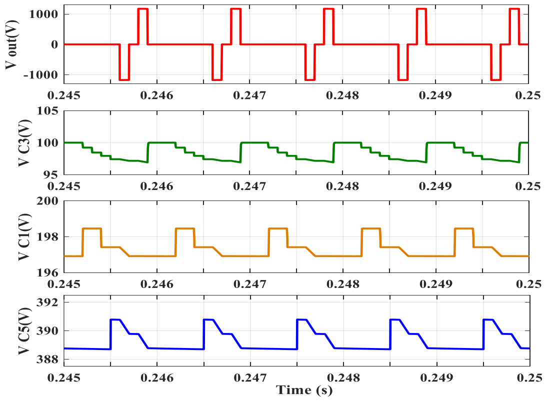


(a)

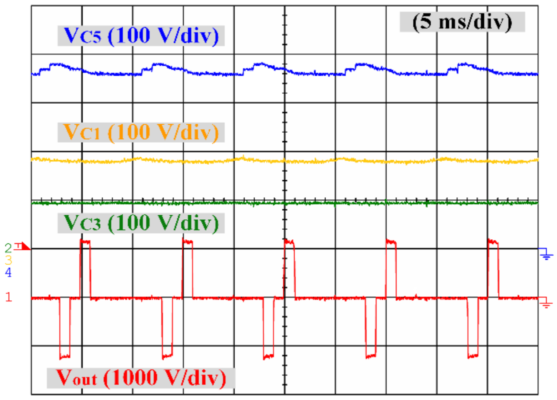
(b)

(c)

Figure 7. The output voltage of the proposed pulse generator, (a) simulation, (b) experimental and (c) its rise time

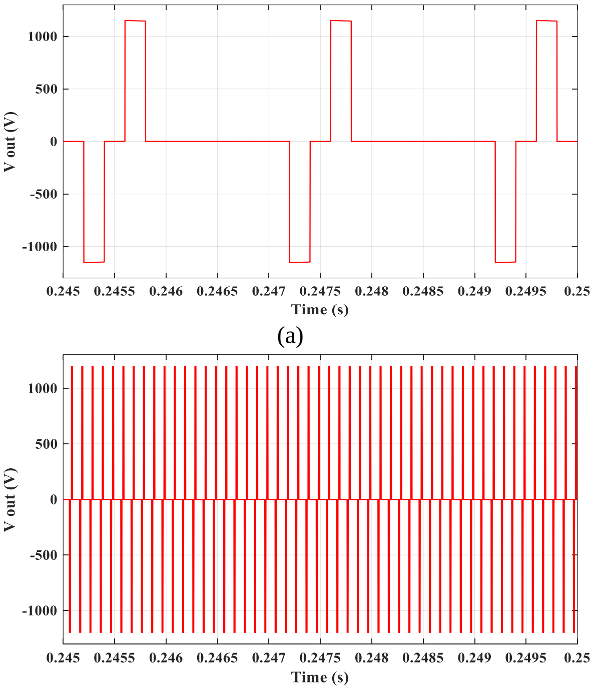


(a)



(b)

Figure 8. The output voltage of the proposed pulse generator, (a) simulation and (b) experimental



(a)

(b)

Figure 9. (a) 50 and (b) 1000 Hz output voltages

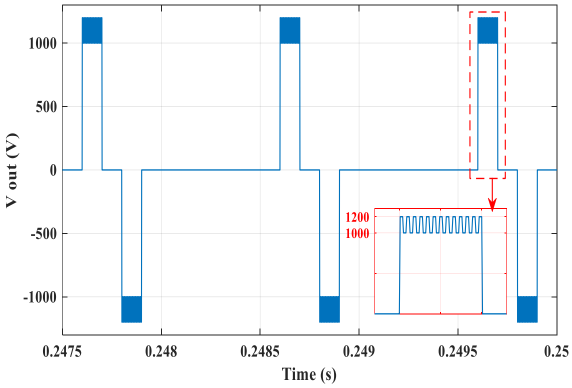


Figure 10. A combination of wide and narrow pulses

4. CONCLUSION

A bipolar pulsed power generator was presented, which can appropriately replace Marx structures in applications with low voltage inputs due to its boosting ability. Circuit topology, operating principles, and different stages of the circuit's operation are presented besides capacitance calculations. Also, the structure was compared to other similar circuits where the results showed that it outperforms them by requiring fewer semiconductor devices to generate the same output pulse. Eventually, simulations were conducted, and by testing a laboratory prototype, a 1.2 kV bipolar voltage pulse was produced from a single DC source with an amplitude of 100 V, whereas it had a 5 µs rise-time. The theoretical bases of the topology, simulation, and experimental results prove the sufficient ability to produce the intended bipolar pulses.

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Persian Abstract

چکیده

این مقاله یک مولد توان پالسی را ارائه می‌کند که می‌تواند یک پالس دوقطبی ولتاژ بالا را از یک منبع ورودی نسبتاً کم ولتاژ، بر اساس مفهوم کلید-خازنی، تولید کند. بر اساس در یک الگوی از پیش تعریف شده، مدار ولتاژ ورودی را با ذخیره انرژی در چندین خازن و آزاد کردن آن به بار به طور همزمان افزایش می دهد. شایان ذکر است که این ساختار بدون استفاده از هیچ کلیدی دوسر بار می تواند ترمینال خروجی خود را در حین شارژ کردن خازن ها، اتصال کوتاه کند. این توپولوژی عمدتاً برای کاربردهایی مناسب است که نیاز به پالس ولتاژ بالا دارند و فقط به منابع ورودی ولتاژ پایین دسترسی دارند. محاسبه و به کارگیری دقیق خازن‌ها تضمین می‌کند که مدار می‌تواند پالس‌های خروجی مورد نظر را با افت ولتاژ قابل قبولی تولید کند. در نهایت، MATLAB Simulink برای ارزیابی عملکرد مدار مورد استفاده قرار گرفت و آزمایش‌های تجربی بر روی یک نمونه آزمایشگاهی انجام شد که نتایج آن، عملکرد مناسب مدار را تایید کرد.