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Flexible output pattern high-power pulse generator

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Abstract. Day by day, the need for renewable fuel has increased to reduce the usage of non-renewable fuels and also to provide adequate fuel for vehicle use worldwide. Organic fuels that can be derived from different sources are renewable fuels, of which oil extracted from algae cells can also be used as a biofuel. Algae oil extraction can be achieved by applying a Pulsed Electric Field across the algae cell to rupture its membrane and to remove oil. A Pulse Generator, capable of carrying out this operation, although in existence, has some drawbacks including lack of versatility, performance and reliability, etc. Pulse generators can also be used for many other purposes, including cancer cell ablation, water treatment, thunder and lightning safety testing of electrical equipment, lasers, radar systems, military, etc. Hence a Pulse generator capable of generating the necessary Pulse patterns, maintaining a reasonable efficiency and performance, including features such as versatility, simple input voltage stepping, high switching frequency etc. The design of a novel solid-state-based topology with the required features is considered to be the main objective of this work. In this paper, we aim to present the design and simulation of the proposed circuit, along with some results obtained. *Index Terms*—Marx Generator, power electronic devices, Pulse circuits, Pulse generation, High power pulse generator (HPPG), Pulse shaping networks.

1. Introduction

This paper deals with solid state version of the H-Bridge fed by Marx's - Generator, capable of producing bipolar as well as unipolar high-powered rectangular Pulses is presented. Although our paper is intended to work for algae cell rupturing, which is based on [1], it can be modified to work for other such applications, which include killing cancer cells using Irreversible Electroporation (IRE), in RADARs, Lasers, food processing industries [2], water purification [3] etc. All these applications require some desired characteristics in the Pulse generating circuit. One of the characteristics is to have a flexible

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output pattern at the output without compromising the component parameters or layout to produce both bipolar and unipolar Pulses with adjustable Pulse width. It's also possible to have adjustable output voltage according to the process requirement.

Price effectiveness is an essential goal in any circuit design. However, because of the severe voltage and power requirements, it becomes a difficult task to attain for high-power and high-voltage applications. In order to produce output at a low cost, efficiency must be within range. This condition is one of the drawbacks prohibiting the proprietary use of the original design by E. O. Marx [4] for high-power Pulse generators because the resistors that are needed cause losses. Other topologies [5] include the use of inductors rather than resistors in cascade with capacitors [3], [6], but require high voltage sources and are not suitable for a broad set of applications. On the other hand, in [12] we see important structure built on H-bridge design allowing for versatile control of outputs.

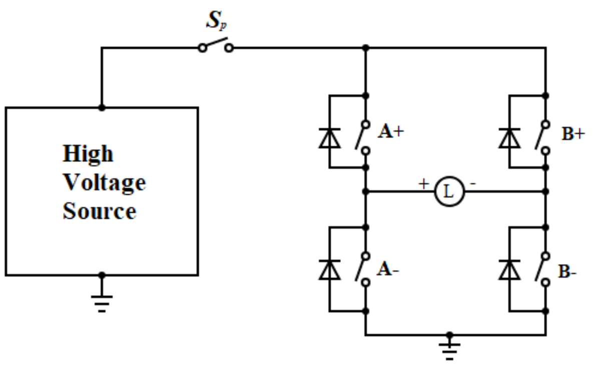


Fig. 1. Proposed Idea for Bipolar HPPG

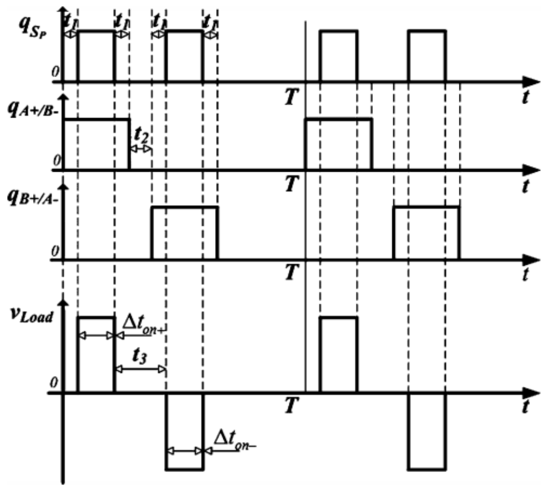


Fig. 2. Switching strategy and voltage at load for Bipolar HPPG

In addition, the input stage consists of cascaded boost-cells, where the capacitors were charged to a level of input voltage, providing more stable and less costly systems. Our circuit uses not only a smaller number of switches but also provides a cost-effective solution by the use of IGBTs (Insulated Gate Bipolar Transistor) in terms of its feasibility in switching which can be changed to our requirement by the control of pulse input to the IGBTs (as opposed to spark gaps used in conventional Marx Generators), also when the output voltage is higher than the switch rating and also the output H-Bridge connection to the load which facilitates bipolar Pulses at the output.

2. Concept and Operating Principle

The general concept for the proposed bipolar Pulse generator shown above Fig. 1. The proposed circuit has an H-bridge topology (conventional), allowing for different configurations to attain both unipolar and bipolar pulses of either polarity. Irrespective of the load, it is advisable to make use of freewheeling diodes with the semiconductor switches in the H-Bridge that facilitate the bidirectional current flow due to stray inductances and other undesirable events. The initial stage which provides a high-voltage level is represented as a switch S_p, and high voltage source. The switching strategy is detailed in Fig. 2.

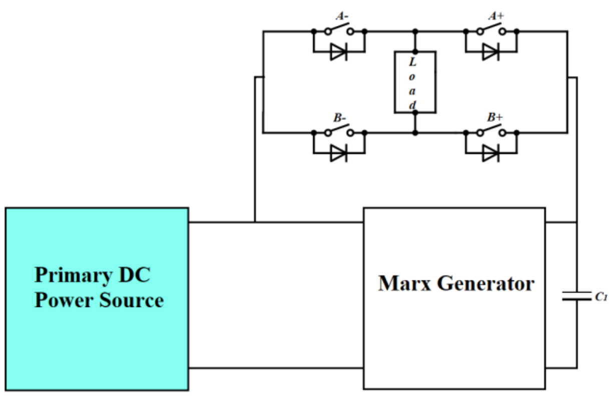


Fig. 3. Marx Generator and H-Bridge parallel connection.

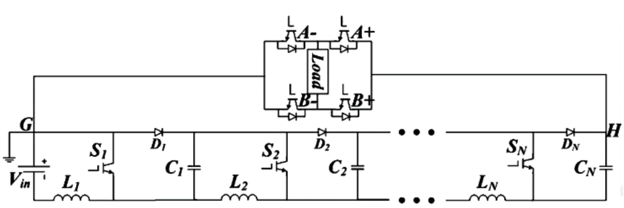


Fig. 4. Topology of bipolar Marx's – Generator (proposed)

This kind of strategy is for altering current through load by distributing high voltage source switch S_p conducting time seen above in Fig. 1 which is between the switches pairs of H-bridge *A+/B–* and *A–/B+*. Therefore, voltage polarity and pulse application were controlled with H-bridge switches and input switch S_p respectively. For achieving (bipolar

Pulses), switches $A+$ and $B-$ were first turned ON, next $B+$ and $A-$ were turned ON typically with equal intervals after $A+$ and $B-$ were turned OFF. As indicated in the above figure, the (S_p) switch gets into the ON condition if and only if any one of the switch pairs of H-bridge were charged into conducting state. Also in Fig. 2, the unipolar pulse operation is taken as a distinct study of bipolar pulse generations where one of the H-bridge pairs of the opposing switches was switched ON. Though both the switches, S_p and H-Bridges have different commutation periods, it is advisable to have a time delay t_1, shown in Fig. 2 due to three reasons. The foremost reason is to violate the high switching losses owing to H-Bridge conduction. The second one is to avoid a high voltage spike at the beginning in the opposite polarity of the Pulse when switch S_p is conducted before the H-Bridge switches, which occurs due to unwanted interactions and ringing between low inductances and the H-Bridge internal capacitances. The last reason is to allow sufficient time for parasitic inductances in the circuit for discharging through another path. A dead time t_2 is also added as shown in Fig. 2, to omit shoot-through currents owing to immediate conducting intervals of H-Bridge switches of the same leg. Thus, our circuit has a total dead time of t_3, resulting from the combination of dead time t_2 and twice the delay time t_1.

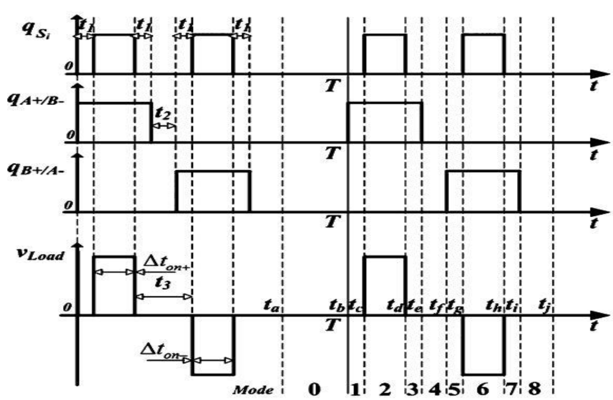


Fig. 5. Modes of operation - timeline diagram of the bipolar solid-state Marx's – Generator (proposed)

The proposed concept of a Pulse generator (bipolar) is supplemented by analysing the high voltage mentioned in the Fig. 1. The high - voltage source turned as an energy barrier that stores energy from a low power supply and, with a short high power impulse, releases it to the charge. Many other topologies [6] use *LC* ladder circuits to produce a rectangular Pulse, but they require a high-voltage source to store energy itself because it is not capable of stepping up the input voltage. Another solution uses a DC-DC converter which increases the voltage of inputs. However, this method needs an intermediate transformer of high frequency for achieving the required step-up conversion ratio [7], [8] but it limits the pulse raise and fall times due to the intermediate transformer's leakage inductances. Therefore, our solution uses a Marx-Generator, where capacitors are connected in parallel while charging and discharging them in series to obtain a stepping-up voltage at the load, but some other topologies [11] using this scheme use more switches than the proposed topology and are less effective and some topologies cannot generate bipolar Pulses. Hence our topology uses this Marx Generator to produce a rectangular bipolar high-power Pulse along with an H-Bridge output stage, and its simplified schematic is as shown in the Fig. 4. It consists of n-number of boost cells to the input voltage multiplication around H-bridge terminal. Though this kind of prototype circuit so proposed requires n number of capacitors,

(n + 4) number of controlled switches, n number of diodes, the voltage obtained at the output terminals increases the Pulse generating (bipolar) topology offered here and needs several capacitors and (*6n)* otherwise less number of switches say (*5n)* number of controlled switches and n number of diodes) depending on the output load requirement. For the circuit seen in Fig. 4, the total of *6n* number of switches includes n number of controlled switches and diodes in the above shown Marx circuit, and (*4n)* or say less number of IGBT's / diodes for the H-bridge, where (*4n)* controlled number of switches considering the each leg would require (*2n)* or say less stacked IGBT's so that the H-bridge stage could maintain the same full Marx's output voltage while using high number of voltage levels. If n is greater than three, in certain other topologies [9], [10] the semiconductor devices total used here is close to that in here. However, the suggested topology still has some advantages given reduced developmental costs and increased reliability, as uses only one capacitor lesser than the aforementioned topologies.

3. Analysis of the circuit

3.1 Circuit Analysis

For analysing the circuit function shown in Fig. 4, during a single switching cycle, the following conditions are assumed:

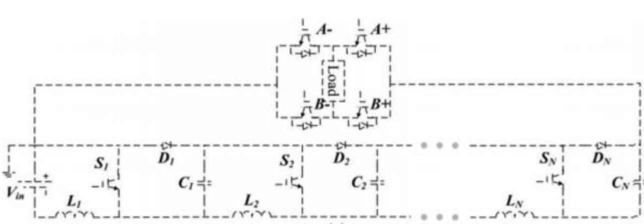
1. The conduction spans for the Si switches are too short to make sure that inductors were not fully charged when the switches were ON,
2. Si switches are quick than H-bridge switches in the cascaded high-voltage source stage,
3. The duration t_3 is short.

Based on these premises, nine distinct modes appearing in Fig. 5 are distinguished from the switch timing.

Circuit working can be portrayed as dependent on given below nine modes of operation.

Mode 0: *Fig. 6(a);* $t_a < t < t_b$: The premise is that the input voltage is first charged with all the capacitors. Therefore, the diodes are all reverse-biased and the currents of the inductors are zero. Likewise, it is guided to turn OFF all semiconductor switches. Soon after this, zero voltage appears at the output, since no current flows in the circuit.

Mode 1*: Fig. 6(b);* $t_b < t < t_c$: $A+$ and $B-$ are turned on before capacitors are connected in series for smooth operation in the H-bridge circuit. The corresponding circuit is shown in Fig. 6(b) with S_i switches OFF and diodes gets reverse biased. As the C_N capacitor is held at the level of input voltage, the output voltage is zero and no current flows in the circuit.



(a)

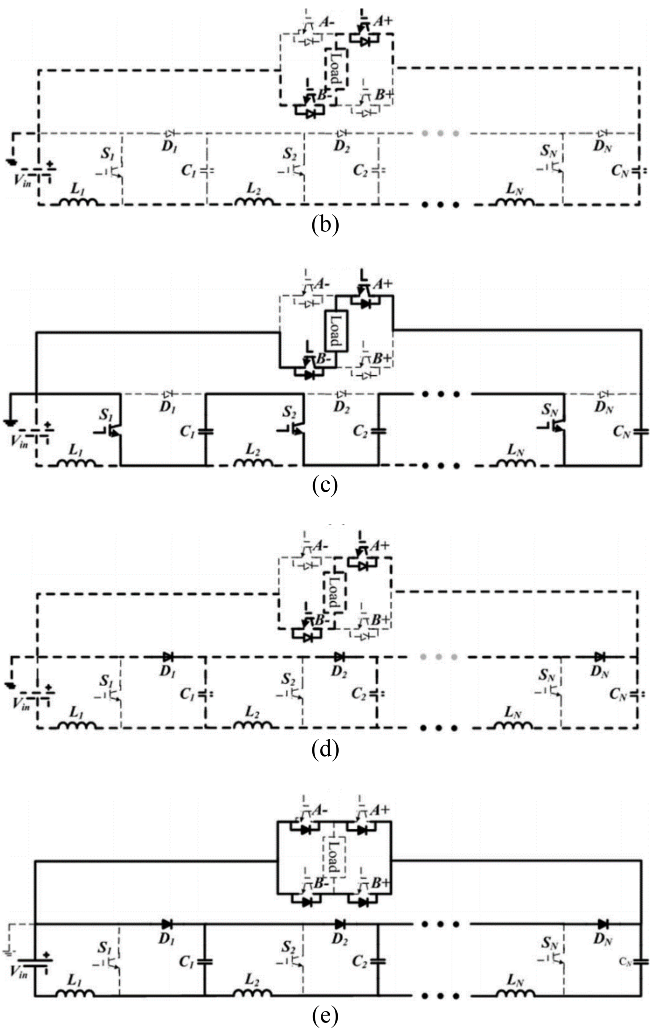


Fig. 6. Modes of operation of the solid-state Marx generator (bipolar). Thick traces indicate the circulating sizable currents while dashed thick traces indicate the path for circulation of potential current or small currents. (a) All switches turned off: Mode 0 (b) $A+$, $B-$ turned on: Mode 1 (c) $A+$, $B-$ and S_i turned on: Mode 2 (d) $A+$, $B-$ turned on; S_i turned off: Mode 3 (e) A, B and S_i turned off; S_i initially turned on: Mode 4, 8.

***Mode 2**: Fig. 6(c); $t_c < t < t_d$:* Once, if S_i switch is turned on, then the boost stages diodes be forward-biased and the Pulse with low output voltage than the minimal voltage output is applied at the load. At the point where the rest of the switches are switched on, then diodes will experience reverse recovery current of moderately high load currents, that would cause critical ringing if the required suppression measures are not carried out. One of the choices that can be made is to use snubbers. Be that as it may, this arrangement may, apparently, reduce system efficiency.

$$v_o = NV_{in} \tag{1}$$

Hence, the current at the output be

$$i_o = \frac{NV_{in}}{R_o} \tag{2}$$

But, because of the equivalent capacitance existence

$$C_e = \frac{1}{\sum_{k=0}^{N} 1/C_k} = \frac{C_i}{N} \tag{3}$$

In (3) C_i reflects that the capacitances in the source circuit which remains same. If at all the parasitic inductance circuit is discharged smoothly, over voltages may emerge. This discharge is achieved as the H-bridge switches were already ON, then after S_i switches will be OFF. The discharge is made via H-bridge switches and then through diodes D_1 to D_N.

Mode 3: *Fig. 6(d);* $t_d < t < t_e$: Is has clearly been explained, $A+$ and $B-$ were switched off in t_1 seconds after all the switches S_i were found OFF. Be that as it may, despite what occurred in mode one operation, little currents even then flow due to interactions between the circuitry parameter, parasitic inductors and discharge of the inductors which is normally the case in the booster converter where the main switch is opened.

Mode 4*:* *Fig. 6(e);* $t_e < t < t_f$: After H-bridge switches turned off, the diodes begin to work, thus facilitating a pathway for current flowing through inductor. On the off chance that the length of this stage is longer, the capacitors may be charged to the input voltage level. In the case of $N > 2$, the diodes of H-bridge will also charge C_N.

Mode 5, 6, and *7: Fig. 6(b)–6(d):* Modes 5, 6, and 7 were equal to modes 1, 2, and 3, then again, literally now instead of $A+$ and $B-$, switches $A-$ and $B+$ were ON. Consequently, (1) and (2) are replaced, respectively, by

$$v_o = -NV_{in} \tag{4}$$

$$i_o = \frac{-NV_{in}}{R_o} \tag{5}$$

Mode 8: *Fig. 6(e);* $t_e < t < t_f$: Mode 8 is the same category as mode 4. Yet, at present, the mode duration is pretty enough to settle down. That is the way, in Fig. 6, the capacitors were charged upto their voltage level at input and inductors were discharged completely, allowing all circuit current to vanish, as seen in mode 4, the voltage at output is equal to zero.

3.2. Design Calculations

Mode 2 and 6 are the defining design modes for the capacitances due to the fact that the capacitors are discharged in these modes. On the off chance that an adequate drop in the voltage (Δv) is defined during discharging, either mode 2 or 6 at that point, the total capacitance (C_e) produced by all the capacitances connected in series of the circuit shall be as:

$$C_e = \frac{I_o \Delta t_{on}}{\Delta v} \tag{6}$$

Assuming linear change in the voltage — a statement that is now true due to the short period of mode 2. In (6) Δt_{on} is equivalent to $\Delta t_{on}+$ or $\Delta t_{on}-$ which can be seen in Fig. 5. Therefore, from equation (3) and taking into account, $I_o = V_o / R_o$

$$C_i = \frac{N\Delta t_{on}V_o}{R_o\Delta v} \qquad (7)$$

and from (1)

$$C_i = \frac{N^2\Delta t_{on}V_{in}}{R_o\Delta v} \qquad (8)$$

It may well be agreed that L_1 charges are fast enough during mode 8 so that only L_1 and C_1 affect the charging procedure of L_1. In this way, when i_{L_1} reaches its maximum, the charging time of L_1 can be approximately one-quarter of the time compared to the oscillation produced by L_1 and C_1 interaction.

$$\Delta t_{ch} = \frac{\pi\sqrt{L_1C_1}}{2} \qquad (9)$$

Due to the numerous collaborations between energy storage components, the inductor discharge period is difficult to acquire analytically from Fig. 6(e). Nonetheless, it could be predictably assumed that the discharging period for L_1 will be lesser than half that of the resonant, duration its outer path in the Marx's stage, including N number of inductors connected in series and then, last C_N capacitor. As a result, the discharging time could be approached,

$$\Delta t_{disch} = \pi\sqrt{NL_1C_n} \qquad (10)$$

Inductance upper limit be obtained by taking into account the condition that L_i should have been completely discharged before mode 0 starts. Consequently, the switching period (T_s) will be more than the summation of the periods in (9) and (10) resp. In these lines, inductance's upper limit is as:

$$L_i \leq \frac{T_s^2}{\pi^2(0.5+\sqrt{N})^2 C_i} \qquad (11)$$

While inductance lower limit could be obtained, given that i_{L1peak} shall be lower than the peak rating of the power supply (I_{max}). Therefore, the lower limit of L_i is as follows:

$$L_i \geq \frac{(\pi N\Delta t_{on}V_{in})^2}{4R_o^2I_{max}^2C_i} \qquad (12)$$

4. Simulations and Results

4.1. Simulations

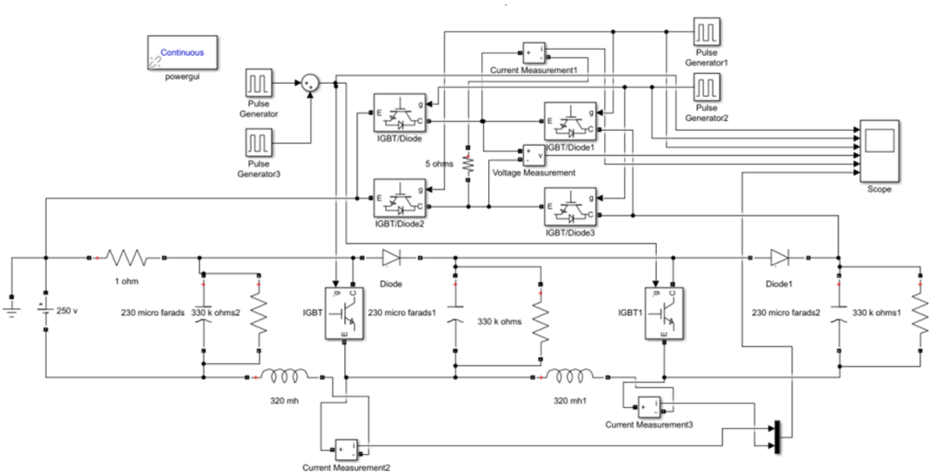
The circuit is intended to work at a frequency of 10Hz, due to the necessities associated with the algae testing. This circuit can likewise be changed to work at an alternative frequency for the need with other applications, including killing of cancer cells utilizing Irreversible Electroporation (IRE), water purification treatment etc. It was picked to set a Pulse width Δt_{on} of 8μs with t_1 = 1μs and t_2 = 3μs. As Fig. 7(a) demonstrates, the load resistance is 5Ω and V_{in} equals 250V which yields a Pulse of 500V amplitude for a 2-stage circuit, 1000V amplitude for a 4-stage circuit and 2000V amplitude for an 8-stage circuit. The circuit diagrams for the 4-stage and 8-stage models can be build and 8 stage is appeared in Fig. 7(b). The capacitances were chosen equal to 230μF yielded from (8) with a voltage drop of up to 12.5V. The maximum DC current obtained at the input stage is about

6.5A and the cycle period is 100ms, which, from simulations, showed that the suitable estimation of inductor value is L = 320mH. The simulations were accomplished for both unipolar and bipolar circuit configurations to obtain both unipolar and bipolar output voltages.

4.2 Simulation Results

The simulation results displayed show the switching strategy of the circuit stage switches and the H-Bridge switches, along with the output current and voltage waveforms. The simulation results indicate that the output voltage of the circuit, as anticipated, is increased by the number of Marx generator stages present in the circuit times the input voltage, during the circuit ON time (Δt_{on}) along with the current.

Figure 8(a) shows the output of a 2-stage bipolar semiconductor Marx generator. As seen, the 2-stage model's output voltage was increased by two times the input voltage, i.e. the output Pulse has a magnitude of 500V. Since the load resistance is 5Ω, the output current Pulse is 100A in magnitude and follows the output voltage shape as the load is resistive. The circuit outputs a total power of 50 kW in the duration Δt_{on}. Likewise, the outputs of Marx's 8-stage generator model are also shown in Fig. 8(b). As described above, for the 8-stage model, 2000V. The output current Pulse has a magnitude of 200A for the 8-stage model, since the load resistance is 5Ω, it has an output current Pulse magnitude of 400A. The circuit outputs a total power of 800 kW in the duration Δt_{on}. The control strategy is modified to activate only the H-Bridge configuration positive or negative group switches to produce unipolar positive or negative output Pulses, respectively.



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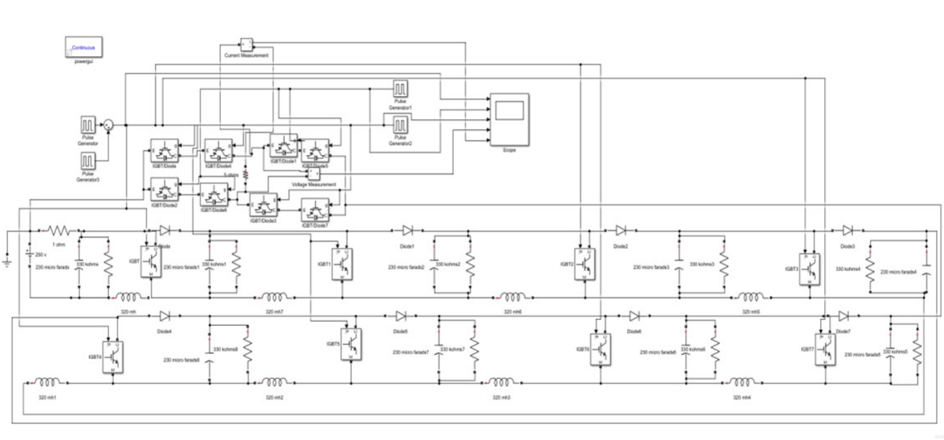
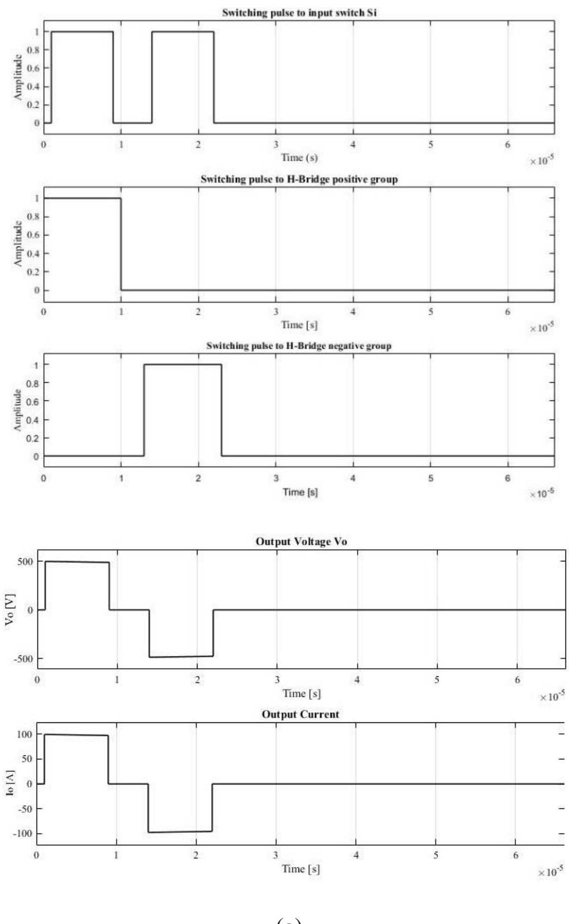


(b)

Fig. 7. Simulation circuit diagrams of bipolar semiconductor Marx's generator topology for the different number of stages. (a) 2-stage bipolar semiconductor Marx's generator circuit. (b) 8-stage bipolar semiconductor Marx's generator circuit.



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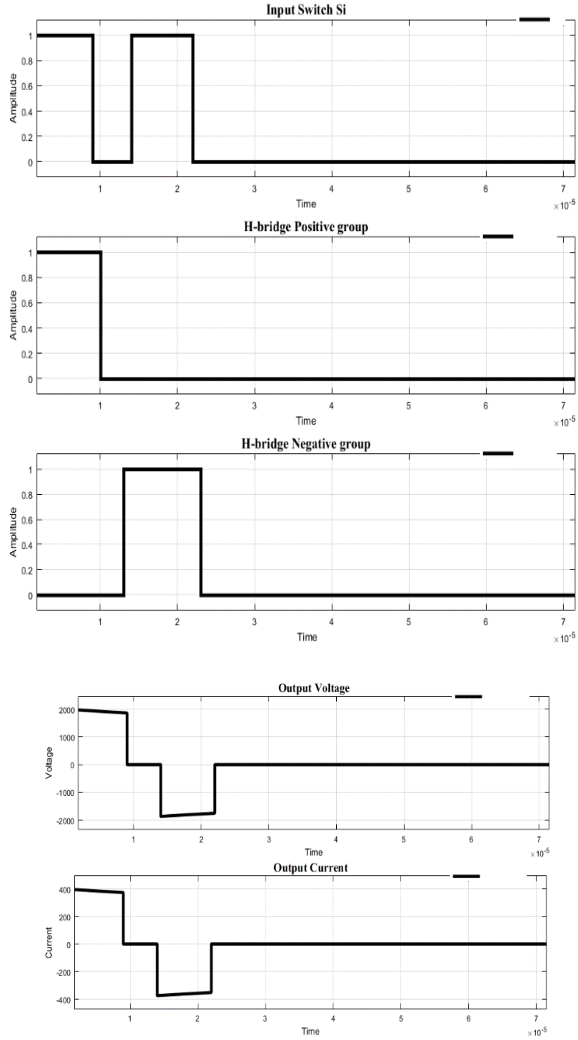
Input Switch Si
Amplitude
Time
H-bridge Positive group
Amplitude
Time
H-bridge Negative group
Amplitude
Time
Output Voltage
Voltage
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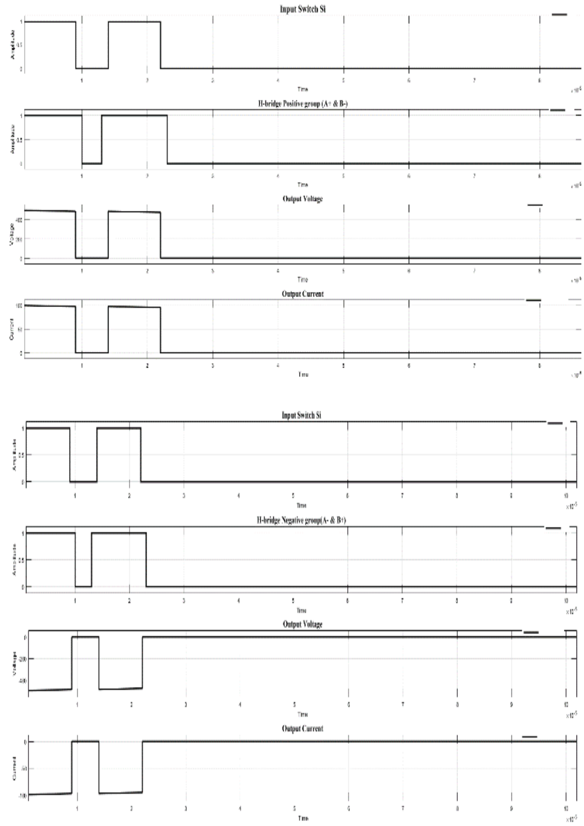
Output Current
Current
Time

(b)



(c)

Fig. 8. Simulated waveforms of different stage bipolar semiconductor Marx generator. (a) 2- 2-stage topology output waveforms showing switching plan, output current and voltage (b) 8-stage topology output waveforms showing switching plan, output current and voltage (c) The unipolar output of semiconductor Marx generator topology producing both positive Pulses and negative Pulses.

5. Conclusion

A rectangular bipolar Pulse generator was presented and analysed in the paper. While our paper is intended to function for the rupture of algae cells, it can be modified to function for other such applications, including ablation of cancer cells using IRE, use in RADARs, lasers, food processing industries, water purification, etc., which requires both unipolar and bipolar rectangular Pulses. The topology proposed is to generate rectangular pulses with stepping of input voltage. The system is economical as well as removes losses (resistive) from conventional Marx generators. The circuit proposed in this paper is incredibly flexible in order to be able to generate multiple Pulse patterns such as unipolar and bipolar Pulse patterns by manipulating the control signals and by not having to reconfigure or reconnect any of the circuit parameters or alter its topology.

The study and design considerations of the proposed bipolar Pulse generator are clarified by mentioning the equations required to pick the inductance and capacitance values. This paper shows 2-stage and 8-stage versions with output voltages of ±500V and ±2000V respectively. We can obtain output voltage for the N number of stages, i.e., $V = NV_{in}$, where N is the number of cascaded LC phases. Another added benefit in terms of usability is that it is still possible to operate even when one of Marx's topology switches fails, but with lower capacity. The stated Marx's generator topology makes it possible to stay away from the necessity of transformers (high-frequency) characteristically used in high-voltage stepping up power supplies, that would usually restrict the pulse rising and falling periods. Another advantage of the bipolar Pulse generation is the organic test results of the rupture of the algae cell membrane, which show that the bipolar Pulse patterns can produce twice the output rate of the unipolar pattern.

Future scope will also concentrate on extremely proficient gate drive circuit's ideal for applications where the conduction Pulse is small, within a range of nanoseconds.

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