RESEARCH ARTICLE

SAMRIDDHI Volume 13, Special Issue 2, 2021 Print ISSN : 2229-7111 Online ISSN : 2454-5767

Design of PFN Based Bipolar Marx Generator

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Abstract

Pulsed power technology is widely used in many fields like medical, military, environmental protection, food preservation, etc. One of the important applications of Pulsed power in the Medical field is in Electroporation. In irreversible Electroporation(IRE) high voltage pulses are applied across cancer cells which kills the cells and hence can be used to destroy the tumour/ cancerous tissue. For irreversible electroporation , Unipolar or Bipolar High Voltage Pulses are used. Bipolar high voltage pulses are preferred for IRE because they can target specific tissue or cells. Also it is found that bipolar pulses don't cause muscle contraction. This paper is regarding the designing of a Marx generator fused with pulse forming network (PFN) to generate high voltage bipolar pulses. The designed generator will have the capability of producing pulses with a voltage up to ±3kV, pulse width of 500ns, and repetition rate of 1 KHz for resistive load of 100&!. The input voltage is 1kV DC. Given design is of six stages and five sections.

Keyword: Marx Generator, Pulse Forming Network (PFN), Irreversible Electroporation (IRE), Rectangular Pulse, Bipolar Pulse.

SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology, (2021); DOI : 10.18090/samriddhi.v13spli02.28

Introduction

Cancer is the second leading cause of death in the world. Cancer is a collective term given to a condition when a certain group of cells divide uncontrollably and spread to the surrounding tissues and cause dysfunctional disorders which can later lead to death. There are currently many treatments which are used to cure cancer like surgical resection, radio frequency (RF) and microwave (MW) ablation, chemotherapy, etc., however not all treatments can be applied to all kinds of cancer[1]. Irreversible Electroporation is one such possible treatment where high voltage pulses are applied to the affected tissue which opens up the pores of the cell membrane irrecoverably and results in cell death. This technique can be used to kill the tumor cells [2]. To generate high voltage pulses many different topologies of high voltage (HV) pulse generator are available. Out of all kinds of HV pulse generators, Marx Generator is widely famous.

A conventional Marx generator is an electrical circuit which is used to produce high voltage pulse from a low voltage DC supply [3, 4]. In a conventional Marx generator, the basic principle of operation is that a certain number of capacitors are charged in series up to a certain voltage V and then suddenly discharged due to which an output of nV is obtained at the load, where n is the number of capacitors used [5]. Conventional Marx generator has spark gaps which are used to connect capacitors in parallel, but constant maintenance and separate circuit for triggering of spark gaps is required. Also, conventional Marx generator gives unipolar pulses [6]. Hence some modification needs to be done to get bipolar

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How to cite this article : Tare, A., Pednekar.A., Thite, N., Nadar, W., Harchandani, R. (2021). Design of PFN Based Bipolar Marx Generator.
SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology, Volume 13, Special Issue (2), 282-287.

Source of support : Nil

Conflict of interest : None

pulses. With advancements in power electronics semiconductor devices, MOSFET, IGBT can be used in place of spark gaps which has no maintenance and can be triggered easily [7]. The paper explains the design and simulation of PFN based bipolar Marx generator. Design and simulation is done for five PFN sections and six stages of Marx to achieve the bipolar pulse of desired width and voltage.

Section II explains the pulse forming network (PFN).

Section III describes about the topology used.

Section IV explains the design of PFN and Marx Generator

In section V simulation result has been described

Section VI concludes the paper

Pulse Forming Network

Pulse parameters cannot be controlled by using only Marx generator. To control pulse parameters, pulse forming networks can be used in every stage of the Marx Generator. Pulse forming networks have key advantage that they are able to store the exact amount of energy which is required for a pulse and discharge energy into the load in a specified pulse shape [8].

A pulse forming network consists of inductors and capacitors connected in ladder network. The PFN supplies rectangular pulses [9] with defined output impedance. To make the top of the pulse flatter and to ensure that the voltage is constant for the maximum duration of the pulse multiple sections of PFN can be used.

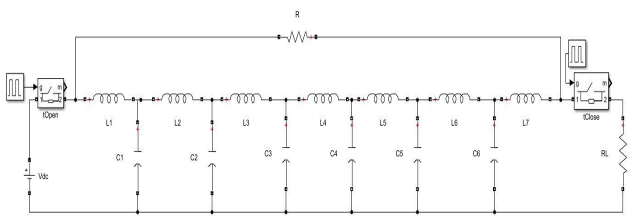

Figure 1: PFN Topology

There are multiple topologies of PFN circuit. The topology showed in Figure 1 is used in our proposed circuit. In this type of PFN circuit, initially tOpen switch is ON, so all the capacitors get charged to supply voltage Vdc. While discharging, switch tClose will be ON, Capacitor C6 will discharge into load through inductor L7 and C1 will discharge through inductor L1 via low resistance path R. Both Capacitors C1 and C6 Discharge simultaneously. Similarly, Capacitor C2 and C5 will discharge simultaneously and Capacitor C3 and C4 discharge simultaneously.

PROPOSED TOPOLOGY

The proposed topology of bipolar Marx generator is shown in Figure 2.

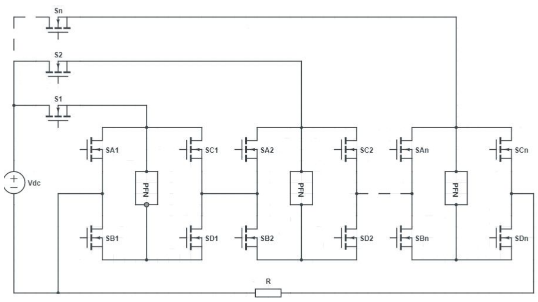

Figure 2: Proposed Topology

The main difference in this proposed topology and topology given in [10] is that this circuit uses PFN network in place of capacitor. In this topology PFN and switches are used to get bipolar pulses. There are four steps of operation

Step 1: Switches S1, S2, . . ., Sn are turned ON and also SB and SD Switches are turned ON. This step charges capacitors to input voltage. In the proposed topology we replace capacitors with PFN circuits. Hence a PFN circuit also gets charged.

Step 2: Switches S1, S2, . . ., Sn and SD are turned OFF followed by switches SC are turned ON. Thus PFN discharges to load and positive pulse is obtained.

Step 3: Switches S1, S2, . . ., Sn are turned ON and also SB and SD Switches are turned ON, switches SC and SD are turned OFF to charge PFN again to input Voltage.

Step 4: Switches S1, S2, . . ., Sn and SB are turned OFF. Switch SD and SA are turned ON. Thus PFN discharges to load and negative pulse is obtained.

PFN Design

The Pulse forming network selected was optimized for pulse power and rise time [8, 11 and 12]. This PFN was selected because of faster response time. The circuit delivers double the pulse power to the load in the same time. Here we have designed a Marx generator of voltage up to ±3kV, pulse width of 100-1000ns, and repetition rate of 1 KHz for resistive load of 100Ω and an input voltage source of 1kV DC. [13]

For design of this PFN following formulae can be used [14, 3]:

Output Voltage of PFN across match load,

$U_L = U_O/2$……..(i)

Energy of PFN,

$E=C^* U_O/2$……(ii)

Pulse Duration,

$\tau = 2\sqrt{(LC)}$……(iii)

Characteristic impedance of PFN,

$Z_M = \sqrt{(L/C)}$……..(iv)

Pulse Power across match load,

$P = U_L * I$……(v)

Where,

U_L – Pulse Voltage

U_O – Source Voltage

τ – Pulse Duration P – Pulse Power

L – Total Inductance C – Total Capacitance

Z_M – Characteristic Impedance

N – Number of PFN Stage

It was found that the resistance of tissue ranges from 80- 200&! [15]. Here we are assuming 100Ω as the load impedance of the Marx generator. Now the input Voltage of the Marx Generator will be 1000V. Hence according to equation (i) the output of each PFN will be 500V [8, 11], so for 3KV output Pulse we would require six PFN Stages.

Characteristics Impedance of six section PFN will be = 2*Load Impedance = 2*100=200Ω

Therefore the characteristic impedance of each section

Z_M = 200/6 =33.334Ω

For Z_M = 33.333Ω, T = 500ns, inductor and capacitor value found out as below:

L= 1.6667µH and C=1.5nF.

The pulse width of the output waveform across the load can be varied by varying the number of PFN sections. In the project, five PFN sections are used as seen in the Figure 3. The output bipolar pulse of nearly 500 V with single stage and five PFN sections is achieved which is seen in Figure 4. The Figure 5 and Fig. 6 respectively shows the expanded positive and negative pulse obtained with single stage of the designed Marx generator.

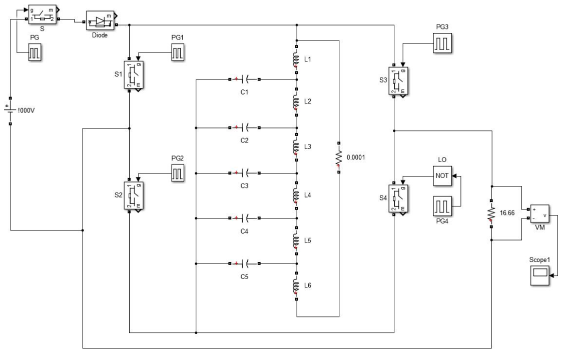

Figure 3: Simulated Model of single stage and five sections bipolar Marx Generator

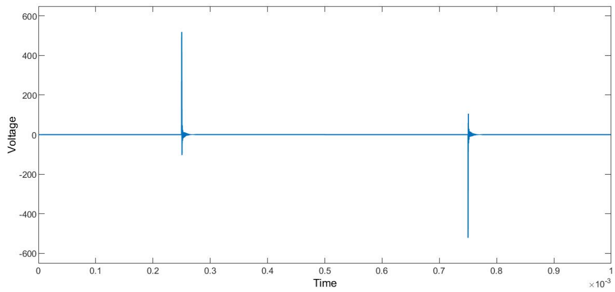

Figure 4: Output of Simulated Model of single stage and five sections bipolar Marx Generator (Approx. 500V)

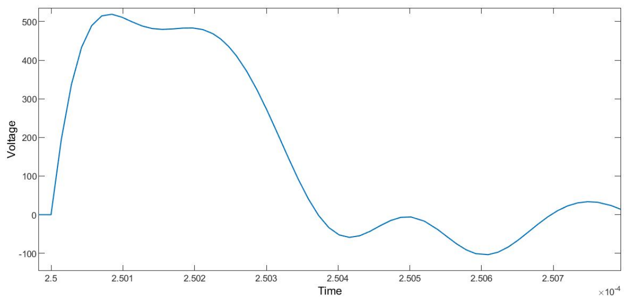

Figure 5: Positive pulse waveform of Simulated Model of single stage and five sections bipolar Marx Generator

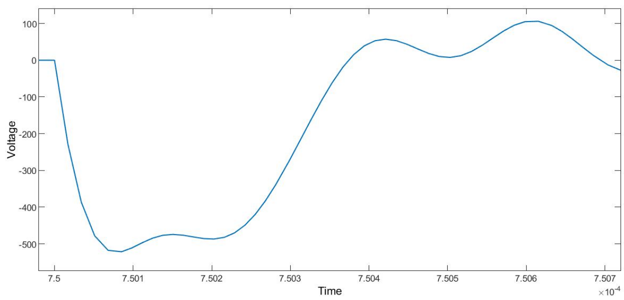

Figure 6: . Negative pulse waveform of Simulated Model of single stage and five sections bipolar Marx Generator

When values of all the inductors are the same the obtained output pulse has an initial peak. It was found that in selected PFN topology if the value of the first inductor is increased then a flatter pulse is obtained i.e. the initial peak is reduced significantly. However, by further increasing the value of inductor rise time increases significantly. Therefore, the optimum value of the first inductor is found out to be 1.8 times the original value.

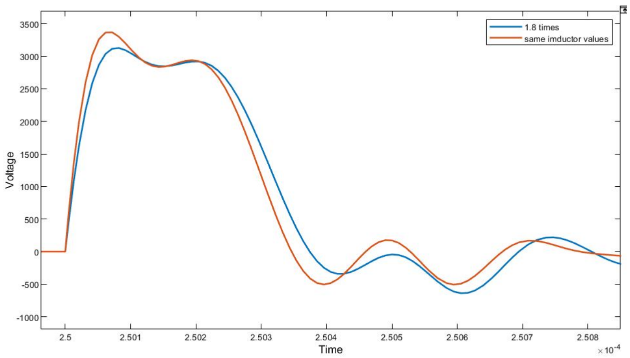

Figure 7: Comparison of pulse shape of PFN when the Value of 1st inductor=1.667μH and when Value of 1st inductor =1.667*1.8= 3μH

The Figure 7 shows flatter peak pulse waveform by using first inductor 1.8 times the rest of inductors in the PFN, superimposed by the waveform obtained by equal values of all the inductors.

Table-1 Shows the pulse width of obtained pulse with change in number of sections.

Table-1: PFN Sections and Pulse width

No. of PFN sections	Pulse width(ns)
2	205.2
3	265.8
4	316.6
5	374.2

Figure 8 and Figure 9 shows positive and negative pulses of output waveform for different numbers of sections. We can see that as the number of sections increase, pulse width increases. Also, the waveform becomes more flat (nearly square wave) as the number of sections increase.

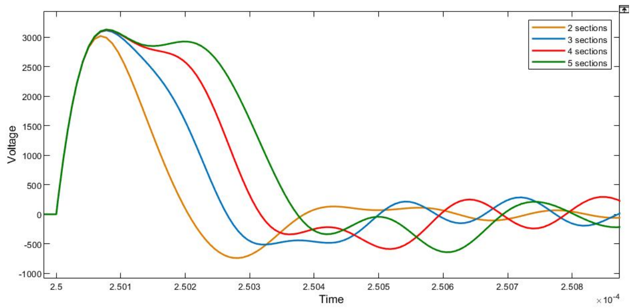

Figure 8: Positive pulse shape with 2,3,4 and 5 PFN sections On X-axis: Time & Y-axis: Voltage

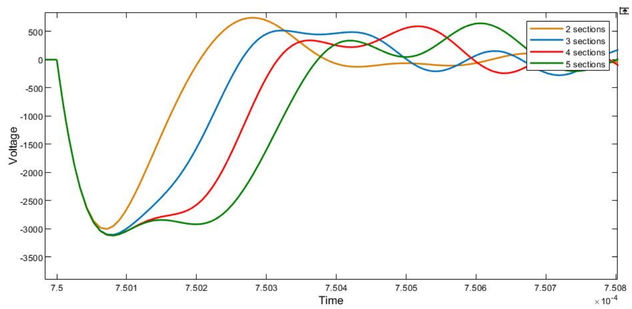

Figure 9: Negative pulse shape with 2,3,4 and 5 PFN sections On X-axis: Time & Y-axis: Voltage

To observe the output voltage with no. of stages, figures 10 and 11 show positive and negative pulses of output waveform for different numbers of stages respectively. We can see that as the number of stages increase, output of the generator increases.

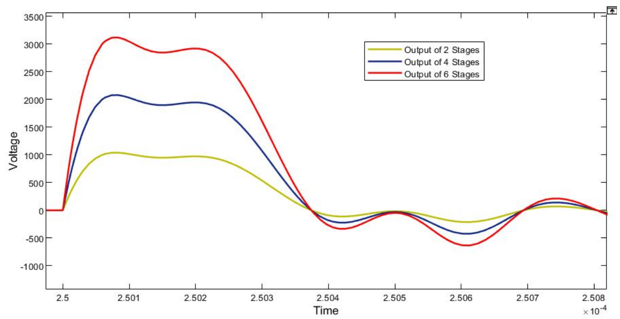

Figure 10: Positive pulse of output voltage for different no. of stages

As per the referred topology expected output of each stage is 500V. Hence for two, four and six stages, simulation output comes out to be 1000V, 2000V and 3000V respectively.

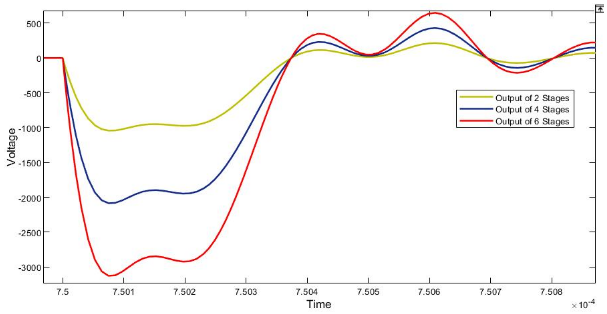

Figure 11: Negative pulse of output voltage for different no. of stages

RESULT

A six stage and five section bipolar Marx generator based on above mentioned topology was simulated. Following Results were obtained.

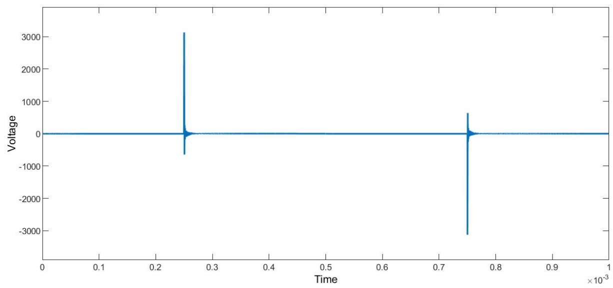

Figure 12: Output Voltage waveform of designed MG, 3kV peak

Figure 12 shows output waveform of bipolar Marx generator with expected output of 3kV desired for selected application. Separate positive and negative pulses are seen in figure 13 and figure 14 respectively. Both positive and negative pulses are of approximately 3kV.

Calculations are done for 500ns pulse and it is found that a pulse of +/- 3kV with approximately 374ns duration is obtained at frequency of 1KHz. Circuit diagram is of six stages and five sections per stage.

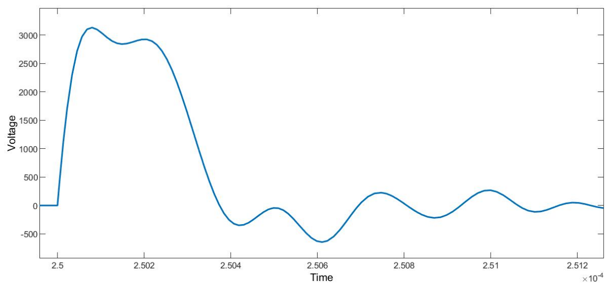

Figure 13: Positive pulse of output voltage waveform across load, 3kV peak

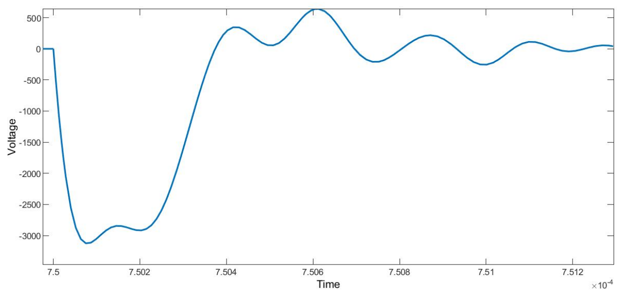

Figure 14: Negative pulse of output Voltage waveform, 3kV

The capacitor used is of value 1.5nF and inductor value is 1.6667μH. As mentioned above the value of the first inductor is taken 1.8 times of the rest inductors to reduce overshoot.

CONCLUSION

This paper describes the designing and simulation of high-voltage nanosecond pulse generator based on solid state PFN based Marx circuit. It is seen that with increase in sections of PFN, we get a better square wave with increase in pulse width. Hence it is better to have more number of sections. But more number of sections will increase the cost and complexity of the circuit. Therefore, five sections are good enough which gives us a pretty decent square waveform and simple circuit. Also, from the results, as the number of stages increase output of the Marx generator increases. Output of each stage is 500V. Hence to obtain required 3000V output, six such stages are connected.

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