# All Silicon Marx-bank topology for high-voltage, high-frequency rectangular pulses


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**Abstract - This paper discusses the operation of a fully integrated solid-state Marx generator circuit, which has been developed for high-frequency (kHz), high-voltage (kV) applications needing rectangular pulses. The conventional Marx generator, used for high-voltage pulsed applications, uses inductors, or resistors, to supply the charging capacitors voltage, which has the disadvantages of size, power loss and frequency limitation. The proposed circuit takes advantage of the intensive use of power semiconductor switches, replacing the passive elements in the conventional circuit, to increase the performance, strongly reducing losses and increasing the pulse repetition frequency. Also, the proposed topology enables the use of typical half-bridge semiconductor structures, while ensuring that the maximum voltage blocked by the semiconductors is the voltage of each capacitor (i.e. the power supply voltage), even with mismatches in the synchronized switching, and with fault conditions. A laboratory prototype with five stages, 5 kW peak power, of this all silicon Marx generator circuit, was constructed using 1200 V IGBTs and diodes, operating with 1000 V d-c input voltage and 10 kHz frequency, giving 5 kV pulses, with 10 μs width and 50 ns rise time.**


## I. INTRODUCTION

Nowadays, high voltage pulsed power supplies have a broad range of applications. One attractive application in surface treatment techniques, particularly, plasma immersion ion implantation (PIII), is a versatile new method for implanting ions, which can be used to modify the surface properties of materials intended to form new compounds and to devise new semiconductors. With this technique, the sample is immersed in a discharge chamber (where plasma is generated) and short, almost rectangular, negative high-voltage pulses are applied to the sample, resulting in the acceleration of the ions into the surface of the sample and further implantation of the material [1]. This and other applications (food treatment, waste sterilisation,…) increase the need of efficient and suitable pulsed power supplies, based on power semiconductor switches and on new topologies brought from power electronics [2].

High voltage pulses can be generated using several techniques. The most widely used one, combines a high voltage power supply with semiconductor switches, either in series or resonant circuit associations to overcome the high voltage limitations of semiconductor devices. Step-up transformers can be applied to further increase the output voltage pulses. However, the transformer non-ideal behaviour worsens the pulse shape [3].

The Marx generator concept [4], as shown in Fig. 1, charging capacitors ($C_i$) in parallel and discharging them in series into the load (through a number of switches, $S_i$), where the subscript $i \in \{1, 2, \ldots, n-1, n\}$, provides another widely used method for generating high-voltage pulses, because it requires only a relatively low-voltage power supply, $V_{dc}$, for charging and does not require pulse transformers to achieve the desired high-voltage.

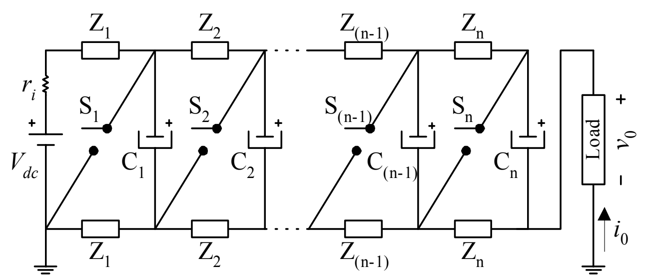


Fig. 1. Basic topology of the EMG circuit, with n stages, for negative output pulses to the load.


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This approach has been used intensively through the years, changing only the switch technology, from spark gaps to vacuum or gas tubes and nowadays to solid-state semiconductors, and alternating resistive charging systems with inductive ones, $Z_i$. These technological upgrades increased the life-time of the circuit and permitted higher pulse repetition frequency, meaning an improved performance [5 - 9].

However, the use of passive elements (resistors or inductors, $Z_i$), as shown in Fig. 1, for charging the energy storing capacitors, $C_i$, and to limit the self-discharging of the capacitors, during the series operation, contributes to the low yield and efficiency of the circuit, limiting the pulse frequency, due to the long charging time constants, and degrading the generation of almost rectangular pulses.

Thus, in the circuit here proposed, Fig. 2, to increase the performance of the classic Marx-bank generator topology, Fig. 1, no charging resistors or inductors are used. Instead, voltage increase is achieved by charging capacitors in parallel, through power semiconductor switches (IGBTs and diodes), and then discharging them in series by opening the charging switches, and closing the discharging ones. The circuit topology and operation mode block any self-discharging capacitor path. Due the power semiconductor topology used, almost rectangular high-frequency pulses can be obtained. Also, the proposed topology enables the use of typical half-bridge semiconductor structures, while ensuring that the maximum voltage blocked by the IGBTs is the voltage of each capacitor (i.e. the power supply voltage), even when the switching is not well synchronized, and even in fault conditions.

A laboratory prototype with five stages, 5 kW peak, of this all silicon Marx generator circuit, was constructed using 1200 V IGBTs and diodes, operating with 1000 V d-c input voltage and 10 kHz repetition frequency. First experimental results show almost rectangular pulses with 5 kV, near 50ns rise time and 10 μs width, giving 1 A into a resistive load.

## II. CIRCUIT TOPOLOGY

The innovative concept, in the Marx-bank type pulse generator circuit present here, is the use of just solid-state switches to charge and discharge the energy storing capacitors stages. For this reason the circuit will be named here as "Electronic Marx Generator" (EMG).

The basic topology of the EMG, with n stages, able to deliver negative high-voltage output pulses to a load, is presented in Fig. 2. Each stage of the EMG consists of a energy storing capacitor $C_i$, a diode $D_{ci}$ and two IGBTs ($T_{ci}$ and $T_{di}$), where the subscript $i \in \{1, 2, \ldots, n\text{-}1, n\}$. Output positive pulses are simply obtained by inverting the polarity of all semiconductors as well as changing $D_{ci}$ with $T_{ci}$, as shown in Fig. 3. In relation to Fig. 2, the circuit in Fig. 3 needs on diode less, $D_{cn}$, and $T_{cn}$ can be replaced with an anti-

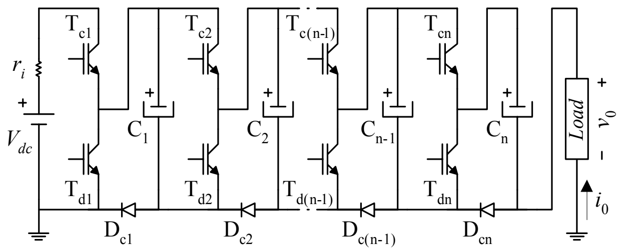



Fig. 2. Basic topology of the EMG circuit, with n stages, for negative output pulses to the load.

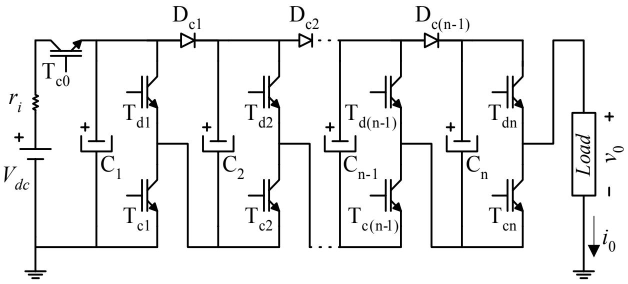



Fig.3. Basic topology of the EMG circuit, with n stages, for positive output pulses to the load.

parallel diode. The inclusion of $T_{c0}$, guarantees that, during the pulse, the power supply $V_{dc}$ is not in parallel with $C_1$.

The EMG operation in Fig. 2 can be understood, considering only two different operating modes. In the first one, switches $T_{ci}$ and $T_{di}$ are, respectively, on and off. During this period, capacitors $C_i$ are charged from the dc power supply, $V_{dc}$, through $T_{ci}$ and $D_{ci}$, as shown in Fig. 4, with current limited by the internal resistance of the elements, resulting in a small time constant that enables kHz operation. The on state of $D_{ci}$ ensures that, during this period, the voltage, $v_0$, applied to the load is approximately zero, as shown in Fig. 6, for a resistive load. Due to the parallel charging topology of the capacitors during this period, the charge currents are larger in the first stages. During starting on, the voltage $V_{dc}$ is slowly increased to limit the charging current on the semiconductors $T_{ci}$ and $D_{ci}$.

In the second operating mode, switches $T_{ci}$ and $T_{di}$ are, respectively, off and on. During this period, capacitors $C_i$ are connected in series and the voltage applied to the load is, approximately,

$$v_0 = -nV_{dc}, \qquad (1)$$

considering that all capacitors are charged with $V_{dc}$, as shown in Fig. 5. However, this holds: *i*) on the characteristics of the components; *ii*) on the operating frequency; *iii*) on the capacitors charge time, $t_c$, being much longer that discharge time, $t_d$, meaning that $T_{ci}$ and $T_{di}$ operate, respectively, with a long ($\delta_c = t_c/T$) and short ($\delta_d = t_d/T$) switching duty cycle, as shown in Fig. 6. The off-state of $D_{ci}$ ensures, during this period, that capacitors are not short-circuited by $T_{di}$ switches.

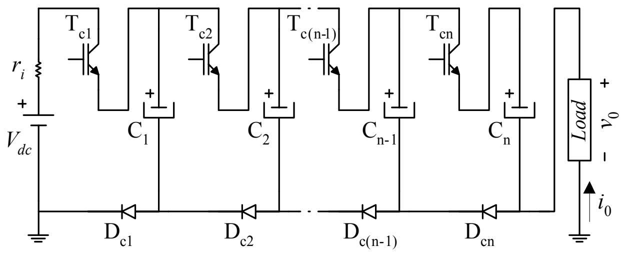



Fig. 4. Capacitors charging operation mode of the EMG in Fig. 2.

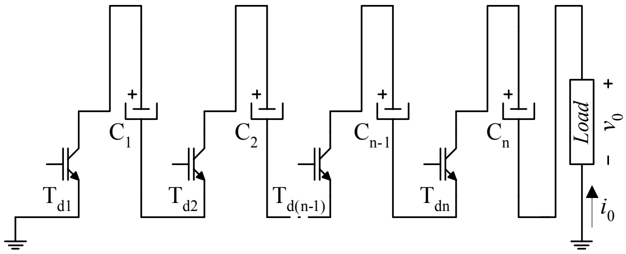



Fig. 5. Pulse operation mode of the EMG in Fig. 2.

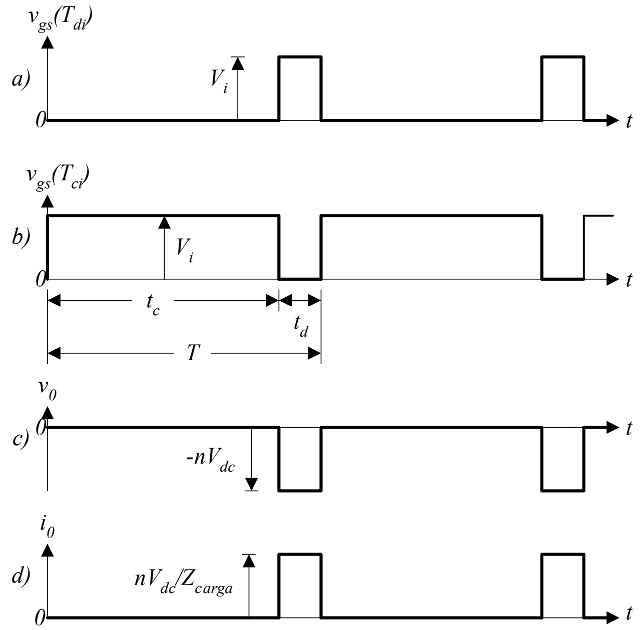



Fig. 6. Theoretical wave forms for the operation of the EMG of Fig. 2, considering a resistive load: a) Drive signal of semiconductors $T_{di}$; b) Drive signal of semiconductors $T_{ci}$; c) load voltage, $v_0$; d) load current, $i_0$.

It is important that, during the pulse, the voltage drop, due to the discharge of the energy storing capacitors, is only a few percent of each capacitor voltage. To guarantee this, the energy stored in the capacitors,

$$E_{cap} = n0.5C_i v_c^2 , \tag{2}$$

where $v_c$ is the voltage in the $n$ capacitors, must be 100 times greater than the energy delivered by each voltage pulse, to the load [2],

$$E_{pulse} = nV_{dc} i_0 t_d , \tag{3}$$

where $t_d$ is the on state period of $T_{di}$ and $i_0$ is the pulse current,

$$i_0 = nV_{dc} / Z_{load} , \tag{4}$$

considering a resistive load and all capacitor charged with $V_{dc}$, as shown in Fig. 6.

For the above conditions, the plateau of the pulse voltage decreases exponentially, during the duration of the pulse, described by

$$v_0 = nV_{dc} e^{(-t/C_{eq}R_{eq})} , \tag{5}$$

where $C_{eq}$ is the capacitance equivalent to the series of $C_i$, and $R_{eq}$ represents the equivalent series resistance of the circuit during this period, which is normally relatively low.

The topology of the EMG, in Fig. 2, guarantees that, if problems with the switching synchronization occur or in faulty conditions, the maximum voltage that each semiconductor holds is $V_{dc}$ (maximum charge voltage of capacitors $C_i$). As an example, if switch $T_{dn}$ switches to on-state somewhat later than the remaining $T_{di}$ switches, diode $D_n$ stays on during this period, maintaining the voltage at the terminals of $T_{dn}$ equal to the capacitor $C_n$ voltage. During this condition the load voltage is, roughly,

$$v_0 = -(n-1)V_{dc} . \tag{6}$$

In addition to the above described advantages, the switching sequence and switch configuration, seen in Fig. 2, enables the use of typical half-bridge semiconductor structures currently integrated in modular packages, which is advantageous to built the circuit and to drive the semiconductors.

Due to the circuit topology, Fig. 2, it is important to avoid cross conduction between $T_{di}$ and $T_{ci}$ switches. Hence, an auxiliary circuit provides a delay time (i.e. dead time), between switching input control signals, so that the turn-on control input to $T_{di}$ IGBTs is delayed with respect to the turn-off control input of $T_{ci}$ IGBTs, and vice-versa.

Also, due to the increase number of semiconductor, in the circuit of Fig. 2 in comparison to the circuit of Fig. 1, the complexity of the driving circuit is enhanced. First, there are two drive signals, $v_{gs(Tdi)}$ and $v_{gs(Tci)}$, respectively, to $T_{di}$ and $T_{ci}$, which must be driven synchronously, Fig. 6. Second, all the switches are at different potentials, requiring gate circuits with galvanic isolation (optic fibres are used to transmit the gate signals).

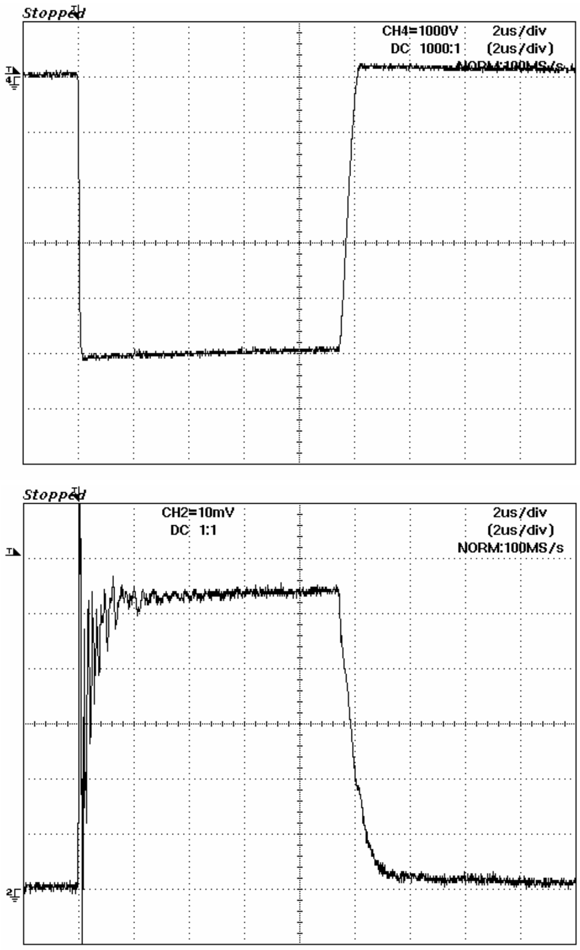
## III. Experimental results

A laboratory prototype of the EMG circuit of Fig. 2, with five stages, 4.5 μF capacitors, was built using 1200 V IGBTs and diodes, operating with $V_{dc}$=1000 V, 10% duty cycle and 10 kHz repetition rate. Fig. 6 shows the pulse pulse, $v_0$, and pulse current, $i_0$, for a resistive load.

The voltage pulse, in Fig. 7 a), exhibit an almost rectangular shape with - 5 kV amplitude and 10 μs width, giving 1 A, into a resistive load, Fig. 7 b). The 10 kHz pulse frequency is observed in Fig. 8 a), and the 50 ns pulse rise time is shown in Fig. 8 b).

## IV. Conclusion

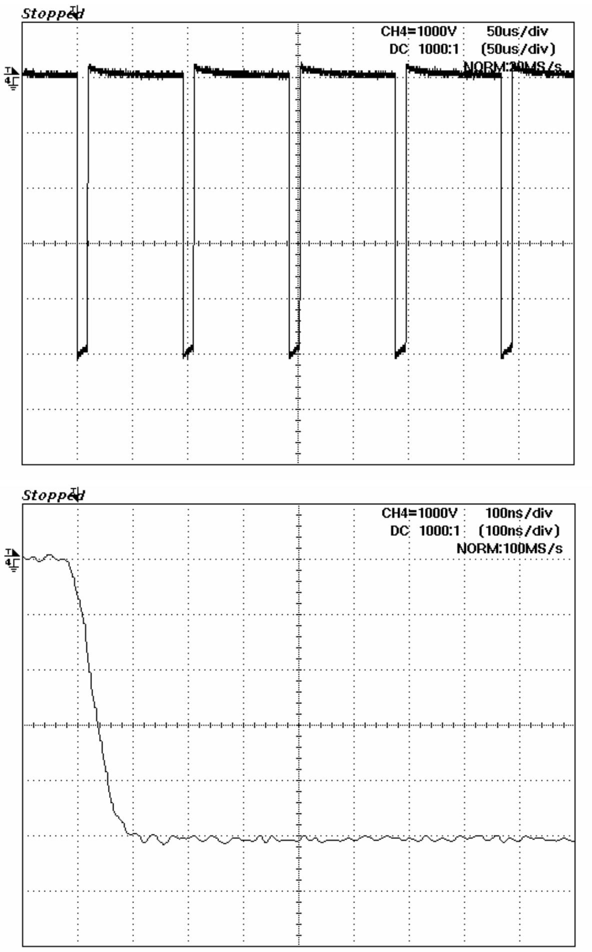
A new all-in-Silicon Marx-bank topology for high-voltage, high frequency pulse generator circuit for rectangular pulsed applications has been proposed. The circuit uses only power semiconductor switches to increase the performance of the classical circuit, where the inductive, or resistive, charging system is replaced by solid-state switches, strongly




a)

b)

Fig. 7. Experimental results for the EMG of Fig.2, horizontal scale 2 (μs/div): a) Voltage pulse, $v_0$, 1000 (V/div); b) Current, $i_0$, 2 (mA/div).




a)

b)

Fig. 8. Experimental results for EMG of Fig. 2, Voltage pulse, $v_0$, 1000 (V/div), horizontal scale: a) 50 (μs/div), b) 100 (ns/div)

reducing losses and increasing the repetition frequency. The proposed topology enables, also, the use of typical half-bridge semiconductor structures while ensuring that the maximum voltage blocked by the IGBTs is the voltage of each capacitor (i.e. the power supply voltage), even when the switching is not synchronized, and in fault conditions.

A laboratory prototype with five stages, 5 kW peak power, of this all silicon Marx generator circuit, was constructed using 1200 V IGBTs and diodes, operating with 1000 V d-c input voltage and 10 kHz frequency, giving 5 kV pulses, with 10 μs width and 50 ns rise time. Using state-of-the-art kV IGBTs and diodes, high voltage pulses reaching dozens of kV can be obtained using the EMG concept.

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