Solid-state Marx generator design with an energy recovery reset circuit for output transformer association

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I. INTRODUCTION

Today, high voltage pulsed power supplies have a wide range of applications [1-4], which increase the need of efficient, flexible and suitable power supplies, based on solid state switches [4].

A number of techniques have been used in order to generate HV pulses from generators with optimised performance and characteristics. Nowadays, the most widely used technique, combines a high voltage power supply with semiconductor switches, either in series or resonant circuit associations to overcome the semiconductors high voltage limitations [5].

The Marx generator concept [6], as shown in Fig. 1, charging capacitors (C_n) in parallel (through resistive or inductive charging elements, Z_n) and discharging them in series into the load (through switches, S_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.

This approach has been intensively used through the years, with significant technological improvements to increase the performance of the original circuit [7 - 12].

Pulse transformers can be applied, in almost all pulsed topologies, to further increase the output voltage. However, the transformer parasitic elements (leakage inductance and distributed capacitance) deteriorate the pulse shape, which worsens with increase the number of turns [13].

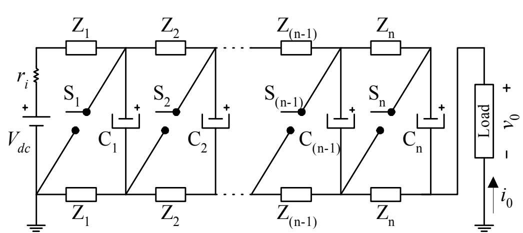


Fig. 1. Basic *n* stages Marx Generator topology, for negative pulses.

Even so, when the voltage is in the order of several tens of kV, due to the still low semiconductor voltage blocking capability, several tens of series solid state switches must be packed in order to hold the high voltage [14]. Hence, when using series semiconductors, complex methods must be used to drive all the semiconductors at the same time, with isolated power supplies. As a result, this high voltage generation technique can be rather challenging to implement.

In this work, we have considered that a compromise approach can be the best way. This points to the use of an hybrid topology, with a Marx generator connected to a step-up pulsed transformer, in order to: *i*) decrease the number of needed solid state switches; *ii*) reduce the turns ratio of the transformer; *iii*) adapt the load impedance to the power supply; *iv*) provide galvanic isolation to the load.

One aspect to consider when using transformers is that the average voltage applied to the windings must be zero. In the case of unipolar pulsed applications, auxiliary circuits must be added to demagnetize the core during the time no pulse is applied, adding complexity to the pulsed circuit [13].

Since the auxiliary circuit is often dissipative [13], the power losses are increased, which contribute to reduce the yield of the pulsed circuit.

To eliminate this drawback, we devised a hybrid fully integrated solid-state Marx generator circuit (Fig. 2), which has been developed for kHz and kV applications needing rectangular pulses. The proposed circuit takes advantage of the power semiconductor switches intensive use, replacing the conventional circuit passive elements, to increase the performance, strongly reducing losses and increasing the pulse repetition frequency [12]. In addition, to further increase the output pulse amplitude, the proposed topology is designed with a magnetizing energy reset circuit that enables the use of an output pulse transformer, and recovers the transformer magnetizing energy, during the off state, back to the energy storage capacitors. This decreases the charging time, and enables higher frequency operation, increasing the pulse generator yield.

A laboratory prototype with five stages, of this all silicon Marx generator circuit, was built using 1200 V IGBTs and diodes, operating with 10 kHz repetition frequency. First experimental results show almost rectangular pulses with -5 kV, 4 to 10 μs width, into a 5 kΩ resistive load.

II. CIRCUIT TOPOLOGY

A. Basic Electronic Marx Generator (EMG) topology

The use, in the Marx generator circuit of Fig. 1, of just solid-state switches to charge and discharge the energy storage capacitors, without the passive elements Z_i, was already an innovative concept presented and discussed elsewhere [12], called EMG (Electronic Marx generator). Fig. 2 shows the basic EMG topology, with n stages, capable of delivering negative high-voltage output pulses to a load (Portuguese Patent, PT-103150). 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 $i \in \{1, 2, \ldots, n\text{-}1, n\}$.

The EMG operation of Fig. 2 can be basically understood, considering only two different operating modes. In the first mode, Fig. 3 a), switches T_{ci} and T_{di} are, respectively, on and off.

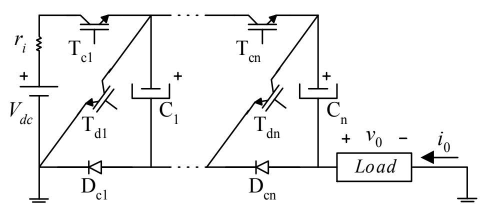


Fig. 2. Basic topology of the Electronic Marx Generator circuit, with n stages, for negative output voltage pulses in the load.

During this mode, the capacitors C_i are charged with total energy, $E_{cap} = n0.5 C_i V_{dc}^2$, from the dc power supply, V_{dc}, through T_{ci} and D_{ci}, with current peak limited by the internal resistance of switches, resulting in a small time constant that enables kHz operation.

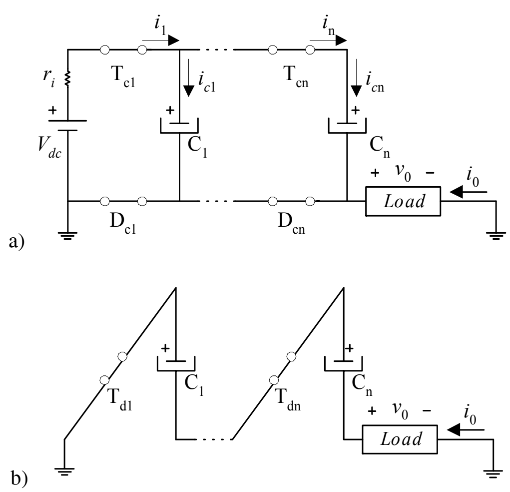


Fig. 3. Operation of circuit in Fig. 2: a) Capacitor charging mode; b) Pulse mode.

In the second operating mode, Fig. 3 b), 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, $v_0 = -nV_{dc}$.

Considering that, the capacitors charge time, t_c, is made much longer than the discharge time, t_d, switches 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.

It is important that, during the pulse, the voltage drop, due to the discharge of the energy storage capacitors, is only a few percent of each capacitor voltage. To guarantee this, the energy stored in the capacitors, E_{cap}, must be approximately 100 times greater than the energy delivered by each voltage pulse, to the load [15], $E_{pulse} = nV_{dc} i_0 t_d$, where t_d is the on state period of T_{di} and i_0 is the pulse current, in a resistive load, with all capacitors charged with V_{dc},, $i_0 = nV_{dc}/Z_{load}$.

Due to the circuit topology, Fig. 2, it is necessary to avoid cross conduction between T_{di} and T_{ci} switches. Hence, an auxiliary circuit provides a time delay (i.e. dwell 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.

B. Electronic Marx Generator with output pulse transformer

The topology of the EMG presented in Fig. 2 can be adapted, with few changes, to accommodate an auxiliary circuit to reset the core of a pulse transformer connected in the output, as shown in Fig. 4. The polarity of the output pulse depends on the polarity of the diode placed on the secondary of the transformer. In the case shown in Fig. 4 the pulses are negative.

Considering circuit in Fig. 2, the circuit in Fig. 4 presents an additional semiconductor switch, T_{dA}, and two more diodes, D_A e D_B, to reset the transformer. Diode D_C placed at the secondary, imposes a single voltage polarity onto the load, in this case negative pulses are obtained on the load.

The operation of Fig. 4 circuit can be understood, considering only three different operating modes, with the simplified theoretical waveforms shown in Fig. 6. In the first mode, Fig. 5 a), switches T_{ci} and T_{di} (and T_{dA}) are, respectively, on and off. During this period, capacitors C_i are charged with total energy, approximately, equal to (1). During this mode, diode D_A is on and guarantees that the voltage applied to the primary of the transformer is approximately zero, as seen in Fig. 6 c). Diode D_C on the secondary of the transformer assures that the voltage applied to the load is also near zero.

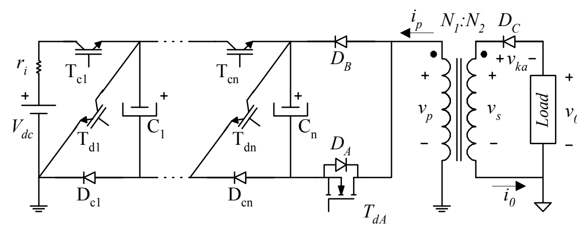


Fig. 4. Topology of the Electronic Marx Generator circuit, with n stages, associated with an output pulse transformer.

In the second operating mode, Fig. 5 b), switches T_{ci} and T_{di} (and T_{dA}) are, respectively, off and on. During this period, capacitors C_i are connected in series and the voltage applied to the primary of the transformer, v_1, is, approximately, equal to, $v_0 = -nV_{dc}$. Diode D_C is on, so the voltage applied to the load is, $v_0 = -nV_{dc}\ N_2/N_1$.

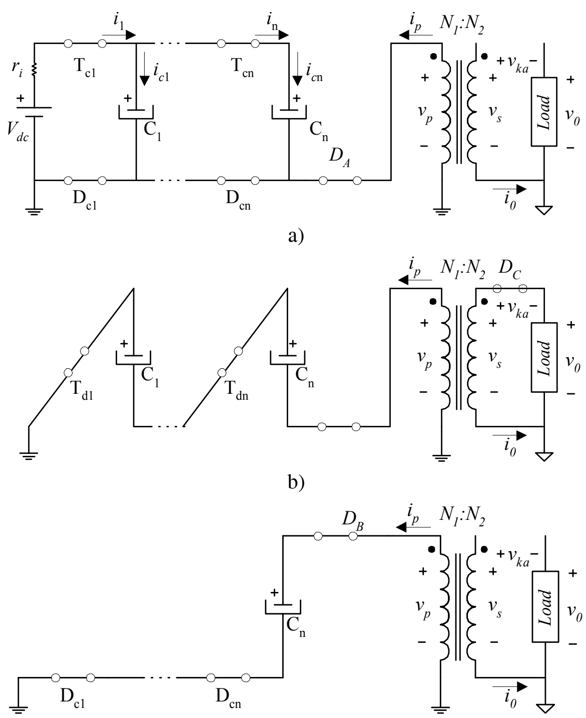


Fig. 5. a) Capacitors charging operation mode; b) Pulse operation mode and c) transformer reset operation mode for the circuit in Fig. 4.

During this period, current i_p, Fig. 6 f), is equal to, $i_p = i_m + i_0'$, where i_m is the magnetizing current of the transformer, and i'_0 is the secondary current reduced to the primary, $i_0' = i_0\ N_2/N_1$.

Considering a linear magnetic circuit, then i_m increases linearly as, $\Delta i_m = nV_{dc}t_d/L_m$, where L_m is the primary magnetizing inductance and t_d is the pulse width, Fig. 6 b). The load current i_0 is given by, $i_0 = v_0/Z_{load}$.

In the third operating mode, Fig. 5 c), switches T_{ci} and T_{di} (and T_{dA}) are off. In the first part of this period, t_a, the voltage applied to the primary of the transformer is, approximately, V_{dc} (Fig. 6 c)) and the magnetizing current i_m has a path through D_B. Since the voltage applied to the primary of the transformer has opposite polarity, i_m decrease linearly, $\Delta i_m = V_{dc}t_a/L_m$.
That, in terms, guarantees the reset of the transformer, sending this energy back to the energy storage capacitors. The capacitor with the lowest voltage receives this current, which increases the capacitor energy. During this period, diode D_C on the secondary blocks a voltage, Fig. 6 e), $v_{ka} = V_{dc}\ N_2/N_1$.

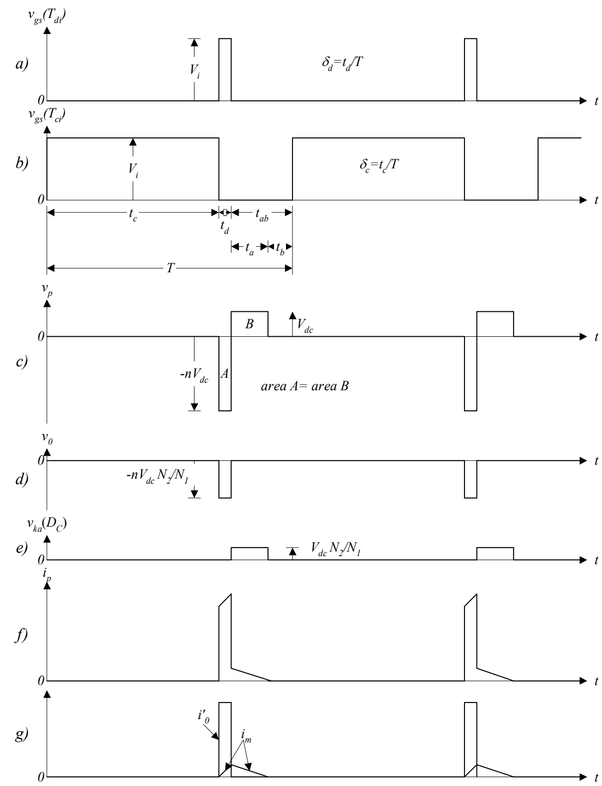


Fig. 6. Theoretical waveforms for the EMG operation with pulse transformer of Fig. 4, considering a resistive load: a) T_{di} drive signal; b) T_{ci} drive signal; c) primary voltage, v_p; d) load voltage, v_0; e) diode reverse voltage, v_{ka}; f) primary current, i_p; g) primary current components.

Considering the power supply voltage constant, V_{dc}, the voltage blocked by D_C is always the same (voltage in each capacitor), independent on the number of stages in the Marx generator. However, increasing the number of stages, the primary voltage is bigger and so the reset time t_a is longer, to guarantee that the volt-second product is equal, Fig, 7 c), during the pulse and during the reset period.

Taking into account Fig. 6 c), after the reset time, t_a, i_m goes to zero and diodes are off. The voltage applied to the primary of the transformer is zero during t_b, after which the first operation mode begins again, Fig. 5 a).

Regarding the drive signals, $v_{gs(Tdi)}$ and $v_{gs(Tci)}$, respectively, of semiconductors T_{di} and T_{ci}, the EMG of Fig. 4 is more complex than the EMG of Fig. 2. Due to the reset period, the drive signals to switches T_{ci} must be delayed by t_{ab}, as can be seen in Fig. 6 b). This difference creates extra complexity for the semiconductors drives.

In both circuits, the semiconductors must be driven synchronously, and as all the switches are at different potentials, it is required gate circuits with galvanic isolation (optical fibres are used to transmit the gate signals).

III. EXPERIMENTAL RESULTS

The purpose of the experimental procedure was to compare the performance of both EMG circuits in Fig. 2 and Fig. 4 to obtain - 5 kV pulses. In order to do that, a laboratory prototype of the EMG circuit, with five stages, 4.5 μF capacitors, was built using 1200 V IGBTs and diodes.

For the EMG circuit of Fig. 2, a power supply V_{dc}=1000 V was used, and the circuit was operated with 10 % duty cycle and 10 kHz repetition rate. Fig. 7 shows the pulse voltage, v_0, into a 5 kΩ resistive load.

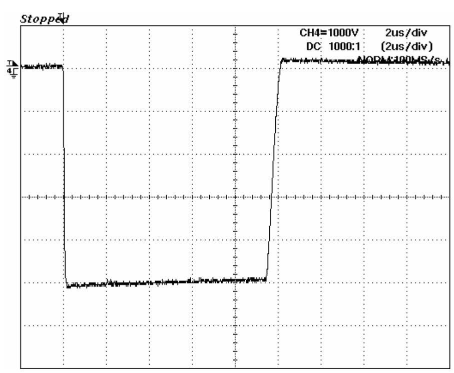
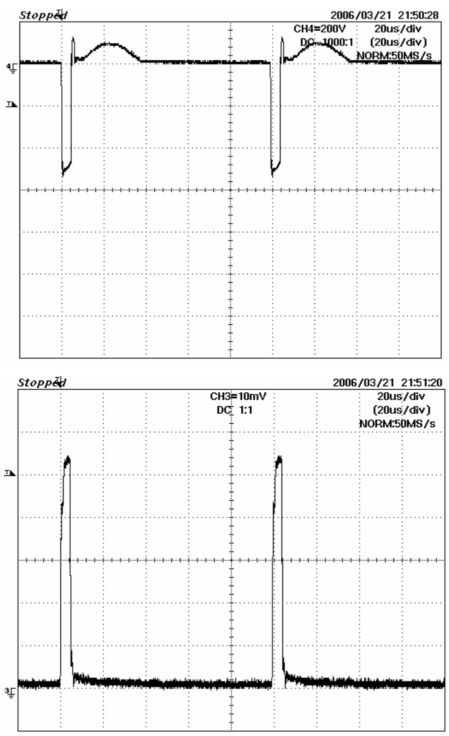


Fig. 7. Experimental results for the EMG of Fig. 2, horizontal scale 2 (μs/div), output voltage, v_0, 1000 (V/div).

The voltage pulse, in Fig. 7, exhibit an almost rectangular shape with -5 kV amplitude, with approximately 50 ns rise time, and 10 μs width, supplying 1 A, to a 5 kΩ resistive load.

For the EMG circuit of Fig. 4, a power supply V_{dc}=100 V was used, and the circuit was operated with 4 % duty cycle and 10 kHz repetition rate. A 1:10 (step-up transformer was associated on the output). Fig. 8 shows the primary pulse voltage, v_p, and primary winding pulse current, i_p into a 5 kΩ resistive load.

It can be seen from Fig. 8 a) that after the 500 V output pulse, with 4 μs width, applied to the primary of the transformer, and opposite polarity voltage is applied to ensure the reset of the transformer. This reset voltage has an amplitude, about, the voltage of the power supply, 100 V (i.e. the voltage on the capacitors, neglecting the losses), and is applied to the primary during the necessary period of time to ensure equal volt-second balance. The wave form of the reset voltage is not squared as it was predicted theoretical, Fig. 6 c), because of resonances between the impedance of the transformer and the capacitors (this waveform is mostly dependent on the magnetizing inductance of the transformer, for lower values of the magnetizing inductance the shape is closer to a rectangle)



a) b)

Fig. 8. Experimental results for the EMG of Fig. 4, horizontal scale 20 (μs/div), primary: a) voltage, v_p, 200 (V/div); b) current, i_p, 2 (A/div).

After the 4 μs pulse, it can be seen, from Fig. 8 b), the slop of magnetizing current, that deceases from is maximum value (≈ 0.3 A) to zero during the reset of the transformer. As it was described above, this current is redirected to the capacitors, recovering the magnetizing energy.

Fig 9 shows the pulse voltage, v_0, applied to a 5 kΩ resistive load. The voltage pulse, in Fig. 9, exhibit an almost rectangular shape with -5 kV amplitude, with approximately 500 ns rise time, and 4 μs width, giving 1 A, into a 5 kΩ resistive load.

The output voltage pulse obtained with the EMG of Fig. 4 has an, almost, 10 times longer rise time, and exhibits more oscillations, as compared with the one obtained with the EMG of Fig. 2, as it was expected due to the use of the output transformer. However, the voltage blocked by the semiconductor switches is 10 times lower. The EMG of Fig. 4 has a diode in the secondary that must sustain the demagnetizing voltage of the transformer reflected on the secondary.

In addition, due two the non-ideal behaviour of the transformer in the circuit of Fig. 4, the circuit in Fig. 2 is more efficient and has less EMI generation.

Therefore, depending on the output pulse voltage needed in a particular application, the number of semiconductors available and their blocking capabilities, the turns ratio of an equivalent transformer to achieve the desirable voltage, the existing power supply voltage and if galvanic isolation is needed, one can choose between the two EMG topologies, here proposed to achieve the best results, with controlled costs.

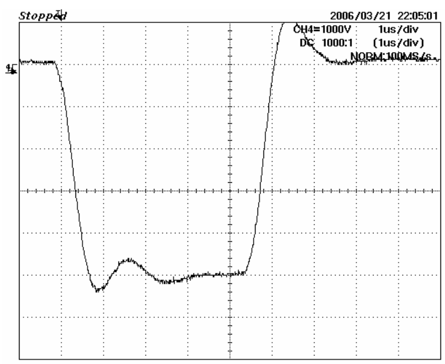


Fig. 9. Experimental results for the EMG of Fig. 4, horizontal scale 1 (μs/div), output voltage, v_0, 1000 (V/div).

IV. CONCLUSIONS

This paper presents a hybrid fully integrated solid-state Marx generator circuit, which has been developed for high-frequency (kHz), high-voltage (kV) applications needing rectangular pulses. The proposed circuit takes advantage of the intensive use of power semiconductor switches to increase the performance of the classical Marx circuit, strongly reducing losses and increasing the pulse repetition frequency. In addition, to further increase the output pulse, the proposed topology is enhanced with an energy recovery reset circuit that enables the use of an output pulse transformer, and recovers the transformer magnetizing energy, during the pulse off state, back to the energy storage capacitors.

A laboratory prototype with five stages of this all silicon Marx generator circuit, was constructed using 1200 V IGBTs and diodes, operating with 10 kHz frequency, giving - 5 kV pulses, with 4 to 10 μs width, giving 1 A into a 5 kΩ resistive load.

The obtained output voltage pulse waveform from the Marx generator with the output pulse transformer has longer rise and fall times. Nevertheless, needed blocking voltages of the switching semiconductors are considerable lower.

Given that pulse shape is not the only important parameter, one can choose between using or not the output transformer to achieve the best results, depending on: 1) needed galvanic isolation; 2) the output voltage pulse needed; 3) the cost of the total number of semiconductors available blocking voltages; 4) the transformer turns ratio needed to achieve the desired pulse voltage; 5) the available power supply voltage; 6) the efficiency; 7) the EMI generation.

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