Voltage Droop Compensation Based on Resonant Circuit for Generalized High Voltage Solid-State Marx Modulator

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***Abstract*— The purpose of this paper is to present and discuss the voltage droop compensation associated with long pulses generated by solid–state bipolar or unipolar high-voltage Marx modulators. In particular a novel design scheme for voltage droop compensation based on resonant circuit in solid-state bipolar (positive and/or negative pulses) high-voltage Marx generator, using off-the-shelf components, design and control, is described. The compensation consists in adding one auxiliary resonant stage to the existing Marx stages, without changing the modularity and topology of the circuit. The auxiliary compensation voltage is added to the output voltage to compensate the pulse voltage droop. Experimental results are presented for five stages Marx circuit, 10% voltage droop, using 1 kV pulse amplitude, 100 µs pulse width, 9.5 ms relaxation time and with 50 Hz pulse repetition rate.**

I. Introduction

The Marx modulator concept is a widely used technique to generate either unipolar or bipolar transient high-voltage pulses from relatively low d-c voltage sources. Recent technological upgrade in the mature Marx modulator concept lead to the intensive use of semiconductor switches, replacing the passive elements and contributing to the compactness of the Marx modulators, capability to generate square pulse shapes, possibility to control the number of pulses, pulse-width, frequency, and the ability to deal with different load conditions [1-4]. In effect, growing variety of environmental, biological, medical, food and industrial applications using repetitive unipolar and/or bipolar high-voltage pulses, for enhancing the characteristics of a final product or method, impose various conditions to the Marx modulators.

One of the most complex conditions to manage is the pulse voltage droop when long pulses are used (i.e. higher then dozens of microseconds), where the output voltage plateau will droop significantly as the Marx capacitors are discharged, unless large size high valued capacitances are used. Instead, several authors have come up with different solutions in unipolar Marx type circuits [5,6], using auxiliary independent cells that are charged during the charging mode of the main capacitors and turned on sequentially to generate corrections to the droop in the main Marx cells. This technique produces discontinuities in the flat top voltage waveform as well as a very complex control system. Other authors [7,8], created an auxiliary circuit called "bouncer", which employs an additional capacitor and inductor to provide an oscillatory, in which part of the resonant voltage is added to the main pulse voltage to compensate the discharge voltage droop. Under this scheme, besides the necessity of an auxiliary power supply to charge the bouncer capacitor this auxiliary circuit has generally a significant design component and cost implication. However, the principle of resonant type voltage droop compensation has not yet been studied in bipolar type generators where sequences of positive and negative pulses are generated.

This paper presents the first results of a novel design scheme of resonant type voltage droop compensation for solid-state bipolar Marx, S^2BM, modulator shown in Fig. 1 and described in detail elsewhere [3, 9].

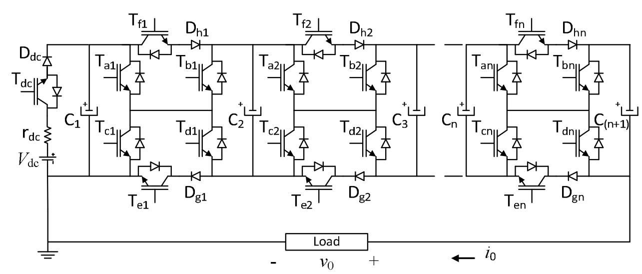

Fig. 1. S^2BM modulator with *n* stages for bipolar or unipolar pulse generation.

To maintain the well known modular characteristic of this topology, one independent auxiliary modulator stage was added, which includes an inductor, as shown in Fig. 2 (particular case of circuit of Fig. 1, without semiconductors D_{hi} and T_{fi}), to perform as a resonant circuit whose voltage is added to the positive or negative pulses to compensate the

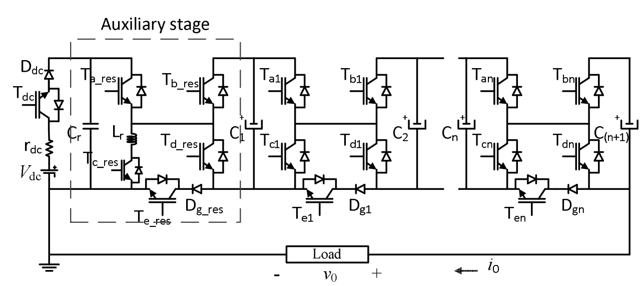

Fig. 2. Tested HV topology of the *n* stages S^2BM modulator, with auxiliary resonant based voltage droop compensation stage for bipolar or unipolar pulse generation, particular case of circuit of Fig. 1.

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discharge voltage droop.

The concept of resonant voltage droop compensation consists in taking advantage of the almost linear part of the sine waveform of the capacitor C_r voltage, where (1) holds.

$$sin(\omega t) \approx \omega t \qquad \Rightarrow \qquad -\pi/6 < \omega t < \pi/6 \tag{1}$$

In order to use only part of the almost linear area of the sine waveform, it was considered that pulses starts at zero resonant voltage, as shown in Fig. 3.

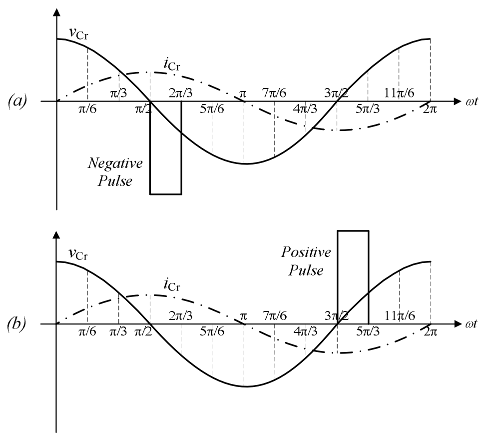


Fig. 3. Resonant circuit voltage and current waveforms and (a) negative and (b) positive pulse starting at zero resonant voltage under almost linear part of the sine waveform.

II. CIRCUIT OPERATION

Fig. 2 shows the proposed circuit topology to deliver repetitive unipolar or bipolar high-voltage output pulses with compensation, comprising n stages and one voltage droop compensation stage, with IGBTs as on-off switches. The circuit of Fig. 2 presents several operating modes. The first one consists in charging the capacitors C_i and C_r through the path consisting by switches T_{dc}, D_{dc}, T_{a_res}, T_{ai}, D_{b_res}, D_{bi}, D_{g_res}, D_{gi}, T_{e_res} and T_{ei} on and all others switches off, as shown in Fig. 4. The next operating mode depends on the required output characteristic imposed by the load. Thus, before applying negative or positive pulse with compensation into a load, it is necessary to trigger on switches, T_{a_res} and T_{c_res} to connect the capacitor C_r in series with inductor L_r to start the resonance through its single cycle sine wave, as shown in Fig. 3. To apply negative pulse with compensation accordingly with Fig. 3a), switches T_{bi} and T_{ci} are turned on at ωt=π/2 (zero resonant voltage). After negative pulse, turning off switches T_{a_res} and T_{c_res} must obey the condition in (2), assuring the continuity of the current and recovery of the energy in inductor L_r back to capacitor C_r, as can be seen in Fig. 3a) and Fig. 4.

$$\pi < \omega\tau < 2\pi \tag{2}$$

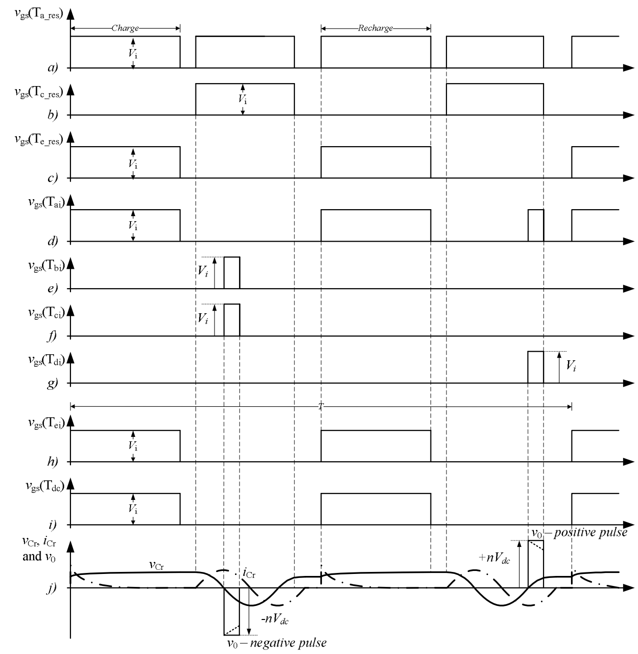


Fig. 4. Theoretical wave forms for the operation of theS^2BM of Fig. 2, considering a resistive load. Drive signal of semiconductors: a) T_{a_res}; b) T_{c_res}; c) T_{ai}; d) T_{bi}; e) T_{ci}; f) T_{di}; g) T_{ei}; h) T_{dc}; i) v_{Cr} , i_{Cr} and output v_0 voltage.

The positive pulse with compensation can be obtained (assuming that capacitor C_r is previously connected in series with inductor L_r, see Fig. 3b)) by switching on T_{ai} and T_{di} at ωt=3π/2 after starting the resonance. After the positive pulse, switches T_{a_res} and T_{c_res} can be turned off safely because the freewheeling diodes of these switches will assure the continuity of the current and recovery the energy in inductor L_r back to capacitor C_r, as shown in Fig. 3 b) and Fig. 4.

III. RESONANT PARAMETERS

In the resonant voltage droop compensation stage the capacitor C_r has same capacitance of Marx stages capacitors C_i. The inductance L_r was calculated taking into account the RLC series equivalent of the resonant circuit. Thus, solving the generic solution of RLC series circuit, (3) is obtained considering that the resistive part (the *on* resistance of the semiconductors) is negligible and the initial conditions of the capacitor C_r voltage and inductor L_r current are V_{dc} and zero respectively.

$$i_{Lr} = V_{dc} sin(\omega_0 t)/(L_r \omega_0) \tag{3}$$

The inductance L_r was obtained, (4), considering that the negative and positive pulses lengths are restrained into intervals given by (5) and (6), for negative and positive pulse respectively, (Fig. 3).

$$L_r > 36 t_{on}^2/(\pi^2 C_r) \tag{4}$$

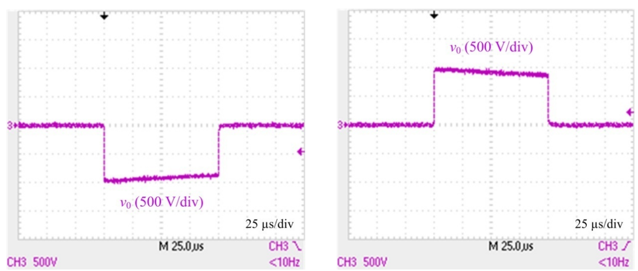
$$\pi/2<\omega t<2\pi/3 \quad (5)$$

$$3\pi/2<\omega t<5\pi/3 \quad (6)$$

IV. Results

A laboratory prototype with five stages of the circuit presented in Fig. 2 was assembled using 1200 V IGBTs (SKW15N120) and diodes (IDB09E120), 4.5 μF for main capacitors and capacitor Cr, 8 mH for inductor L_r, operating with 50 Hz pulse repetition rate, giving 1 kV bipolar pulses, with 100 μs pulse width, and 9.5 ms relaxation time (i.e. time between negative and positive pulses) into resistive load.

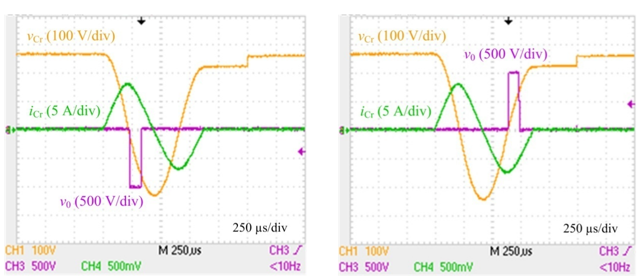
Fig. 5 a) and b) shows the experimental results for the output voltage v_0, into the load, without compensation and 10% voltage droop at the end of the negative and positive pulses.



(a) (b)

Fig. 5. Experimental results for the output voltage of the Fig. 2 circuit, into the load, without compensation and 10% voltage droop at the end of the negative (a) and positive (b) pulse. The scales are 25 μs/div (horizontal) and 500 V/div (vertical).

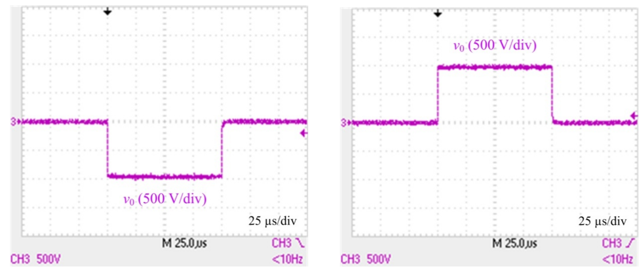
Fig. 6 a) and b) shows the experimental results for the capacitor C_r voltage, current in inductor L_r and the output v_0 voltage with compensation.



(a) (b)

Fig. 6. Experimental results for the capacitor C_r voltage, v_{Cr}, current in inductor L_r i_{Lr}, and the output v_0 voltage with compensation of the circuit of Fig. 2, for negative (a) and positive (b) pulse. The scales are 250 μs/div (horizontal) and 100 V/div (vertical).

In Fig. 7 a) and b) it is shown the experimental results of the output negative and positive pulse voltage with voltage droop compensation with zoomed horizontal scale.



(a) (b)

Fig. 7. Experimental results of the obtained output (a) negative and (b) positive pulse voltage with resonant compensation with zoomed horizontal scale, 25 μs/div (horizontal) and 500V/div (vertical).

V. Conclusions

A new design scheme for voltage droop compensation based on resonant circuit in generalized solid-state bipolar Marx modulator of Fig. 2 was proposed for high-voltage repetitive pulsed power applications.

Keeping the topology of the Marx circuit, an auxiliary stage with inductor was added to the existing Marx stages, which compensates both the positive and negative output pulses. One characteristic of this scheme of compensation is the compromise between pulse repetition rate and the resonant frequency. Other aspect of the circuit of Fig. 2 is that the semiconductor T_{dc} has to hold-off two times the power supply voltage amplitude, V_{dc}. However, the presented topology avoids the need for auxiliary power supply to charge the capacitor of the voltage droop compensation stage, for both the positive and negative voltage pulses. The experimental results obtained from a laboratory prototype, for bipolar output voltage v_0 into a resistive load, shows that the resonant based voltage droop compensation stage is able to compensate a 10% voltage droop both on the negative and positive pulses.

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