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Abstract. The purpose of this paper is to present and discuss a general HV topology of the solid-state Marx modulator, for unipolar or bipolar generation connected with a step-up transformer to increase the output voltage applied to a resistive load. Due to the use of an output transformer, discussion about the reset of the transformer is made to guarantee zero average voltage applied to the primary. It is also discussed the transformer magnetizing energy recovering back to the energy storage capacitors. Simulation results for a circuit that generates 100 kV pulses using 1000 V semiconductors are presented and discussed regarding the voltage and current stress on the semiconductors and result obtained.

Keywords: Bipolar high-voltage pulses, solid-state switches, high-voltage transformer, Marx converter topology, Energy recovery.

1 Introduction

Industries such as food sterilization and wastewater processing have demonstrated an increased interest in high-voltage pulses over the last years. Experience has shown that in most of these cases the use of bipolar pulses results in an improved process performance and in enhanced final products, compared to the obtained with the use of unipolar positive or negative pulses. This represents an additional value to the industrial method and has contributed strongly to the development of efficiency and flexibility of the bipolar high-voltage modulators [1-2].

Considering the techniques that are based on solid-state technology, a frequent method to generate high-voltage bipolar pulses includes the use of two d-c power supplies with series switches, for the positive and negative voltage, which implies the use of series stacks of semiconductors to hold-off the voltage [1, 3]. Also, solid-state multilevel converters have been proposed to generate high-voltage bipolar pulses [4].

The circuit used to obtain high-voltage pulses either unipolar or bipolar is based on the Marx modulator concept. Recent technological upgrading done in the mature Marx unipolar generator concept led to the intensive use of semiconductor switches contributing to a performance increase of the original circuit [5-7]. A generalized solid-state Marx modulator with one low power supply and able to deliver repetitive unipolar or bipolar high-voltage output pulses was presented by [8], shown in Fig. 1.

Hybrid topologies were attained with the combination of Marx generator with a step-up pulsed transformer [9]. This approach decreases the number of needed solid-state switches, reduces the turns ratio of the transformer and provides galvanic isolation to the load.
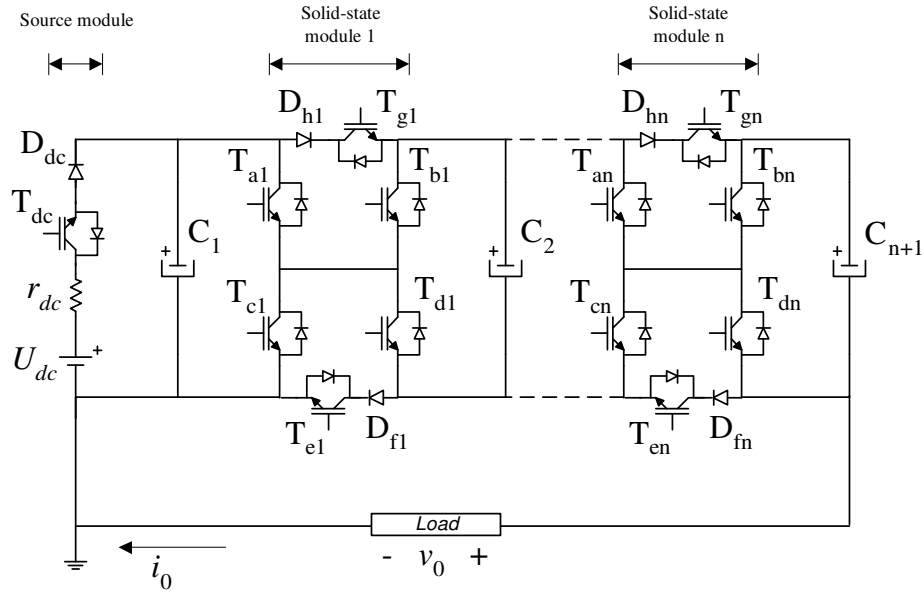

Fig. 1. General HV topology of the n stages solid-state Marx modulator, for unipolar or bipolar generation.

In this work, simulated results and analysis is made regarding the connection of a pulse transformer to the Fig. 1 topology to further increase the pulse amplitude. The reset of the transformer is discussed to improve the circuit performance.

2   Contribution to Value Creation

The connection of a high-voltage pulsed transformer to a solid-state bipolar Marx modulator in order to further increase the voltage in a load is an innovation. If the semiconductor switches are triggered the right way it is possible to reset the transformer core between pulses, recovering this energy to the main capacitors, and at the same time decreasing the reset voltage on the transformer secondary. This will be useful to food sterilization and wastewater processing cutting costs and creating higher quality products.
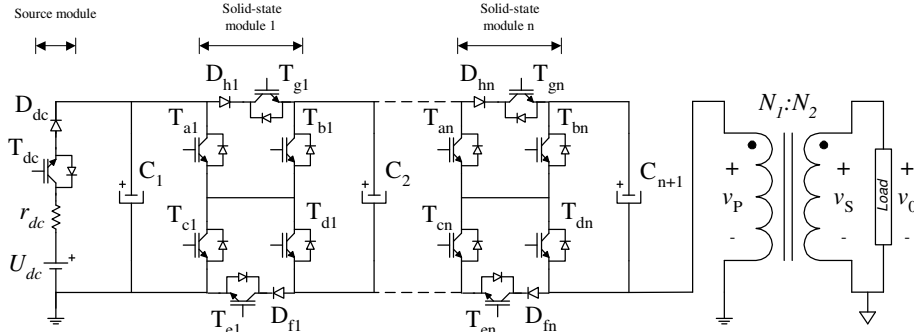
3   Circuit Topology

Fig. 2. Circuit of the Fig. 1 connected to a step-up transformer.

Fig. 2 presents the circuit of Fig. 1 connected to a set-up pulse transformer, aiming the increase by N_2/N_1 of the pulse voltage amplitude applied by the solid-sate bipolar Marx generator into a resistive load.

The Marx topology in Fig. 2 circuit, explained in detail in [8], can be described shortly as a circuit that generates bipolar high-voltage pulses by connecting in series a set of capacitors into a load, previously charged in parallel from a relatively low voltage *dc* power supply, U_{dc}. During the charging mode switches T_{dc}, D_{dc}, D_{hi}, T_{gi}, D_{fi} and T_{ei} are turned *on*. During this period, the *on*-state of the switches T_{ei} and D_{fi}, guarantees that voltage, v_0 applied to the primary of the transformer is nearly zero volts.

The pulse mode operation can be divided in negative and positive pulses. To apply negative pulse into the load, T_{bi} and T_{ci} are switched *on*, being all the remaining switches *off*. During this period capacitors C_i (except capacitor C_1) are connected in series applying a voltage, for *n* stages,

$$v_p = -nU_{dc} \tag{1}$$

to the transformer primary, considering all capacitor charged with U_{dc}, and a voltage

$$v_0 = -nU_{dc} N_2/N_1 \tag{2}$$

applied to the load. During this period, primary current i_p is equal to

$$i_p = i_m + i_0' \tag{3}$$

where i_m is the magnetizing current of the transformer. Considering a linear equivalent circuit with magnetizing inductance L_m, it is

$$i_m = v_p t_p / L_m \tag{4}$$

where t_p is the pulse period and L_m the magnetizing inductance of the transformer, and i'_0 is the secondary current reduced to the primary,

$$i_0^{'} = i_0\, N_2\,/N_1 \qquad\qquad (5)$$

being the load current given by

$$i_o = v_0\,/R_0 \qquad\qquad (6)$$

for a resistive load R_0.

After the negative pulse, the transformer core must be reset with and opposite voltage such that the volt-seconds product is equal to the negative pulse period volts-second. Normally, this is achieved using auxiliary dissipative circuits where freewheeling diodes are used for speediness. The circuit presented in Fig. 2 has natural paths with diodes that accomplished this task, which consists of the IGBTs anti-parallel diodes. Moreover, these paths include the main C_i capacitors whereas the reset circuit is non dissipative, besides the normal losses in the parasitic resistances of the components. Hence, after the negative pulse the magnetizing current of the transformer has a path set by freewheeling diodes D_{ci} and D_{bi} and capacitors C_i (except capacitor C_1), as shown in Fig. 3.
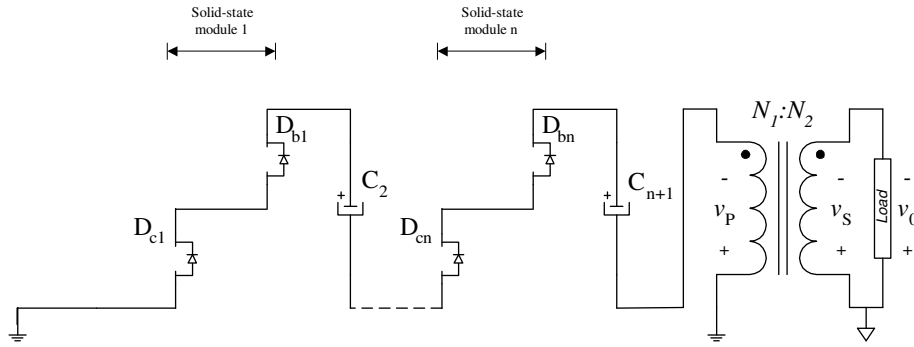

Fig. 3. Transformer reset operation mode of the circuit of Fig. 2, after negative pulse, set by freewheeling diodes D_{ci} and D_{bi} and capacitors C_i (but capacitor C_1).

In this case, during the reset time, the transformer magnetizing energy is recovered back to the energy storage capacitors C_i (except capacitor C_1), and the transformer primary is subject to an opposite polarity voltage with same magnitude of the applied pulse, which is further amplified by N_2/N_1 and applied to the load. This means that two equal amplitude pulses are successively applied to the load with opposite polarity, which is normally not desirable.

Afterwards, when the magnetizing current goes to zero the diodes go off and the reset period is over.

In order to have a lower reset voltage, it is possible to set another path for the magnetizing current to flow after the negative pulse. For example, this path can be set by freewheeling diodes D_{d1}, D_{a1}, D_{hi} (except D_{h1}) and T_{gi} (except T_{g1}) and capacitor C_{n+1}, as shown in Fig. 4. Meaning that is possible to choose just one capacitor to receive the magnetizing energy.
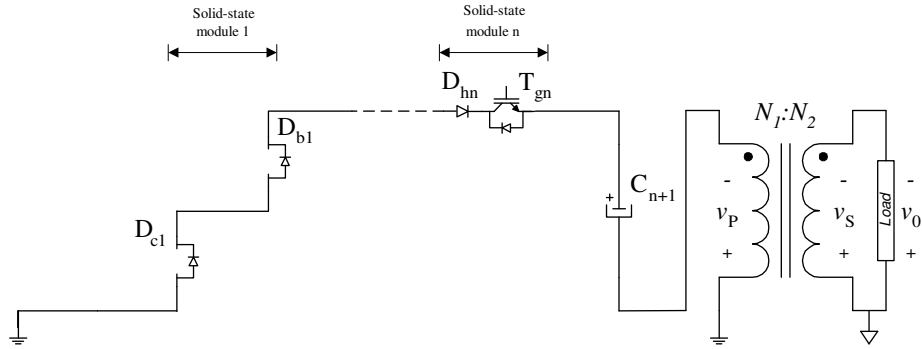
Fig. 4. Transformer reset operation mode of the circuit of Fig. 2, after negative pulse, set by freewheeling diodes D_{d1}, D_{a1}, D_{hi} (except D_{h1}) and T_{gi} (except T_{g1}) and capacitor C_{n+1}, for a lower reset voltage.

For the positive pulse condition the analysis is similar, being the positive pulse obtained by switching *on* IGBTs T_{ai} and T_{di}, being all the remaining switches *off*. During this period, capacitors C_i (except capacitor C_{n+1}) are connected in series.

The natural path to reset the transformer magnetizing energy, after the positive pulse, is set through the freewheeling diodes D_{di} and D_{ai} and capacitors C_i (C_{n+1} is not used), as shown in Fig. 5.
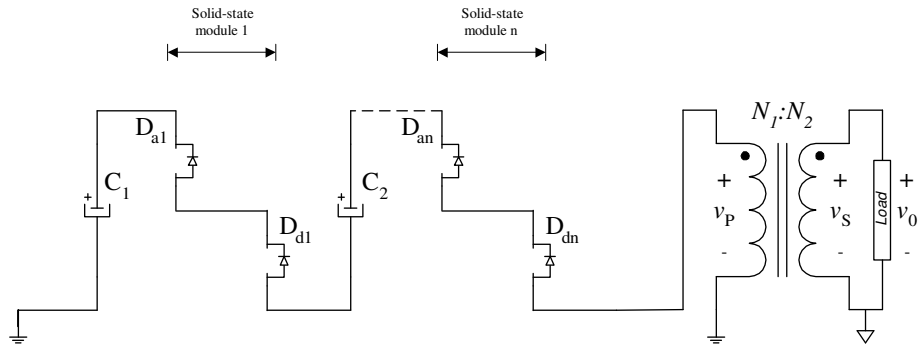

Fig. 5. Transformer reset operation mode of the circuit of Figure 2, after positive pulse, set by freewheeling diodes D_{di} and D_{ai} and capacitors C_i (C_{n+1} is not used).

Again, in reset this condition, the transformer magnetizing energy is recovered back to the energy storage capacitors C_i (except C_{n+1}), and load withstands an opposite polarity voltage with same magnitude of the applied pulse. An alternative way is to use freewheeling diodes D_{dn}, D_{an}, D_{fi} (except D_{fn}) and T_{ei} (except T_{en}) and capacitor C_{n-1}, as shown in Fig. 6.
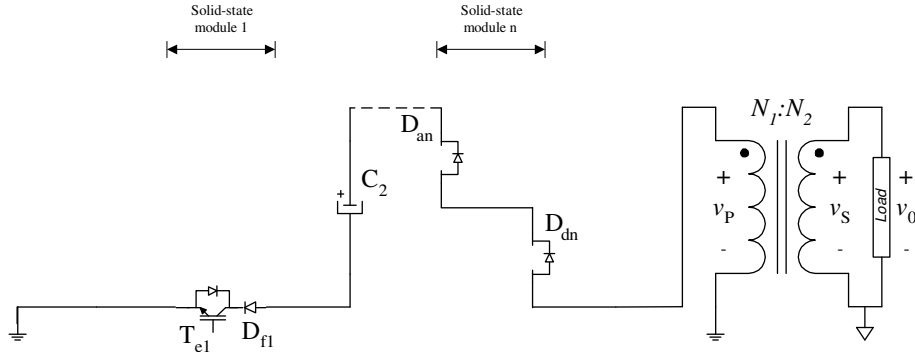
Fig. 6. Transformer reset operation mode of the circuit of Fig. 2, after positive pulse, set by freewheeling diodes D_{dn}, D_{an}, D_{fi} (except D_{fn}) and T_{ei} (except T_{en}) and capacitor C_{n-1}, for a lower reset voltage.

4   Simulation Results

In order to validate the described concept described in the last section, a simulation circuit was designed using SIMULINK/MATLAB software, containing 10 stages Marx generator operating with U_{dc}=1000 V, C_i= 1 µF, and a 1:10 step up transformer, AMCC – 1000, from POWERLITE Inductor Cores, with parameters presented in Table 1, capable of receiving a 10 kV pulse in the primary and delivering a 100 kV pulse in the secondary.

The simulated operating condition were set to 1% duty cycle with 1 kHz repetition rate and 120 µs reset time, into a 100 kΩ resistive load.

Fig. 7 shows the simulated waveform for primary voltage, v_p, and a primary winding pulse current, i_p, into the 100 kΩ resistive load, using all the freewheeling diodes to reset the core with the total voltage.

Table 1. Calculated 1:10 step-up transformer parameters.

N_1	43 turns	R_1	275 mΩ
N_2	430 turns	R_2	28 Ω
L_m	20 mH	V_1	10 kV
L_1	398 µH	V_2	100 kV
L_2	80 mH		

It is shown in Fig. 7 that, in this situation, during the reset period (necessary to guaranty an equal volt-second balance), an opposite polarity voltage is applied into a load with the same magnitude of the pulse. This situation is not wanted as explained above.
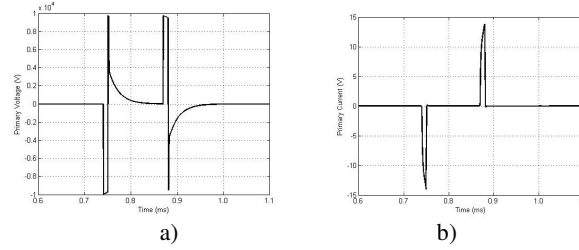
Fig. 7. Simulation results for the circuit of Figure 2 with transformer reset as shown in Figures 3 and 5; horizontal scale 0.1 (ms/div), primary: a) voltage, v_p, 2 (kV/div); b) current, i_p, (5A/div).

If the condition now is set to just one capacitor being used for reset, then the results are obtained in Fig. 8. The difference in the areas of the pulse and reset period are due to energy dissipated. It can be clearly observed the two current components of the primary currents described in (3).

Observing Fig. 8b), the slope of the magnetizing current decreases from its maximum value to zero during the reset of the transformer. As described above, this
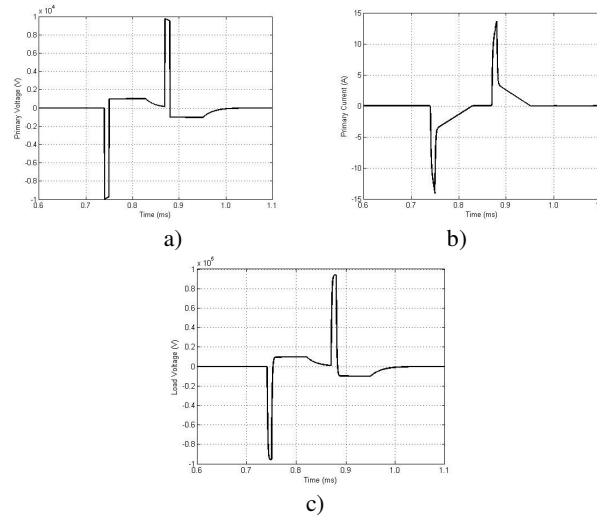

Fig. 8. Simulation results for the circuit of Figure 2 with transformer reset as shown in Figures 4 and 6; horizontal scale 0.1 (ms/div): a) primary voltage, v_p, 2 (kV/div); b) primary current, i_p, (5A/div); c) secondary voltage, v_0, 20 (kV/div).

current is redirected to the capacitors, recovering the magnetizing energy. Fig. 8c) shows the voltage in the secondary of the transformer.

The amplitude of the reset voltage in Fig. 8 is nearly the voltage of the power supply, 1000 V, so the reset time is longer than in Fig. 7.

5 Conclusions

A hybrid integrated solid-state bipolar Marx generator circuit was presented, which associates the advantage of the intensive use of power semiconductor switches to increase the performance of the classical Marx circuit and the advantage of the topology being capable to connect an output transformer to further increase the output voltage. The Marx type bipolar topology used has the ability of recovering the transformer magnetizing energy, during the pulse off-state, back to the energy storage capacitors.

Simulation results showed 10 stages Marx circuit using 1 kV per stage, operating with 1 kHz repetition rate and 1% duty cycle, with a 1:10 step-up, giving 100 kV bipolar pulses at the load and resetting the transformer with U_{dc} after each pulse, recovering the energy to one main capacitor.

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