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A New Family of Marx Generator Based on Resonant Converter

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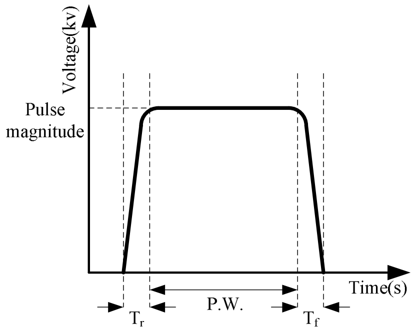
***Abstract* -- This paper presents a novel topology to generate high voltage with utilization of slow and fast power switches. New concepts used in this topology include numbers of diode-capacitor units in parallel with resonant circuits which are connected to a positive buck-boost converter. The resonant circuit reverses the voltage polarity of the capacitors. This configuration has capability of generating a flexible high voltage with certain number of capacitors. The advantage of this topology is to use slow switches, less number of diodes and capacitors compare to Marx generator. Simulations have been performed to verify the proposed topology.**

***Index Terms*-- Pulsed power, Marx generator, High voltage, Repetitively operated pulsed power generator, Resonant converter, Positive buck boost converter, Silicon-Controlled Rectifier, Commutation**

I. INTRODUCTION

Nowadays high voltage systems cover a diverse range of applications; and demand for high voltage power supplies is in a fast growing trend. Pulsed power is one of these applications which require high voltage stress (dv/dt) as well as high voltage magnitude and has been developed for environmental, medical, military and food preservation applications. The pulse attributes vary based on different applications. The pulse widths and voltage levels are mostly in the range of $10^{-10}\sim10^{-5}$ s, and $10^{+3}\sim10^{+6}$ V respectively; depending on the applications. The required energy is defined based on a load demand and varies in the range of $10^{-3}\sim10^{2}$ J. These high voltage pulses with variable pulse widths should have pulse rise and fall times in the low $10^{-9}\sim10^{-7}$ s regime. Pulse repetition frequency depends on loads and applications. Configuration of Fig.1.a clearly indicates the features of a pulsed power. Technologies being used for pulsed power supplies are Marx Generator (MG) [1], Magnetic Pulse Compressor (MPC) [2], Pulse Forming Network (PFN) [3], Multistage Blumlein Lines (MBL) [4] etc. Another topology has been recently introduced in this regard which is based on the buck boost converter concept and employs multi switch-capacitor units at the output. It has the advantage of being more flexible and efficient in term of generating high repetitive pulsed power [5]. Marx generators are the most privilege circuits in pulsed power generation which utilize a simple topology to generate high voltage pulses. A block diagram of a Marx topology is shown in Fig.1.b. In this system, the capacitors are charged in parallel with a DC voltage source up to the input voltage level and then connected in series in order to create a high voltage across a load. Although Marx modulators are in a wide range of utilization, there are still designed and controlled based techniques which can be adopted in their configurations in order to improve their performance in terms of efficiency and flexibility.



(a)

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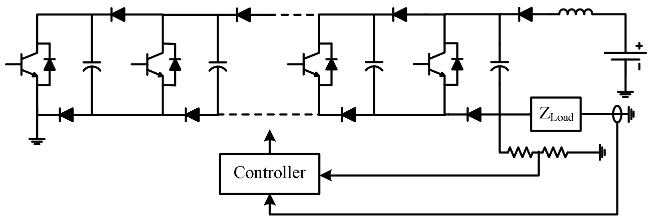

(b)

Fig. 1. (a) Pulsed power features (b) A conventional Marx generator

II. CONFIGURATION AND ANALYSIS

A. Topology

The topology proposed in this paper consists of a positive buck-boost converter as a current source connected to a number of diode-capacitor units as shown in Fig.2. The converter charges the capacitors at a desired voltage level. A new technique is employed to connect the charged capacitors in series and give the summation of the voltages at the output of the system. As can be seen in Fig.2 a full bridge diode rectifier connected to the grid provides a DC voltage for the rest of the system. This Marx modulator has also the potential to be developed for high repetitive pulse applications. Although a repetitively operated pulsed power generator with a moderate peak power needs smaller primary stored energy in comparison with a single shot based pulsed power generator [6], [7], the input source should be able to provide a continuous power supply for the generator. A three-phase rectifier can be utilized for this sake in order to provide primary uninterruptable energy supply from the grid. A positive buck-boost converter is considered in the next stage in order to give the flexibility of boosting the voltage to a desired level. This buck-boost converter is connected to the proposed Marx topology through a power switch. This semiconductor switch disconnects the Marx topology from the rest of the circuit after charging the capacitors.

A detailed circuit diagram of the mentioned topology with diode-capacitor units is shown in Fig.3. As can be seen in this figure, the second and its multiple legs have a resonant circuit including an inductor and a slow semiconductor switch like a Silicon-Controlled Rectifier (SCR). The small inductor is connected to the capacitor through a slow switch to change the polarity of the capacitor voltage. The basic idea of this method is mentioned in [8]. Such an energy exchange behavior known as commutation makes the series connection of the capacitors feasible. In this method the voltage polarity of the capacitors will alternatively be inversed and as a result a connection between these units using a fast switch, S_4 is sufficient for series arrangement of the capacitors. The number of units can be extended with similar connectors in this structure and as a result a higher level of voltage can be achieved at the output of the system.

B. Switching Modes

The switching modes of the proposed converter consisted of four states are shown in Fig. 4.

1), Inductor Charging Mode

In the first switching state, the main inductor, L_1, located at the input of the converter is charged through S_1 and S_2 while S_3 disconnects the rest of the circuit. The charged inductor will act as a current and consequently energy source for the rest of topology in the following operation modes.

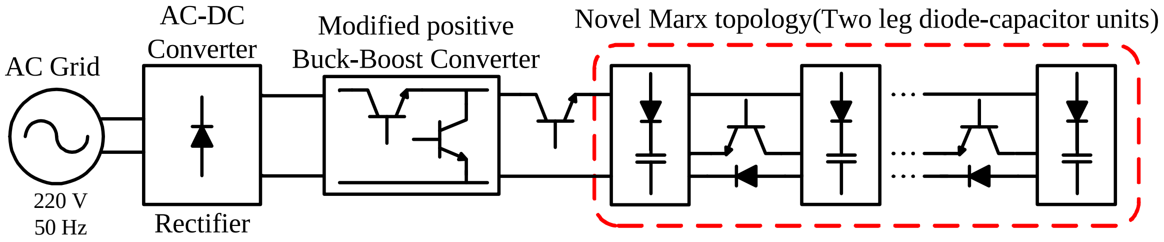

Fig. 2. General block diagram of new Marx topology

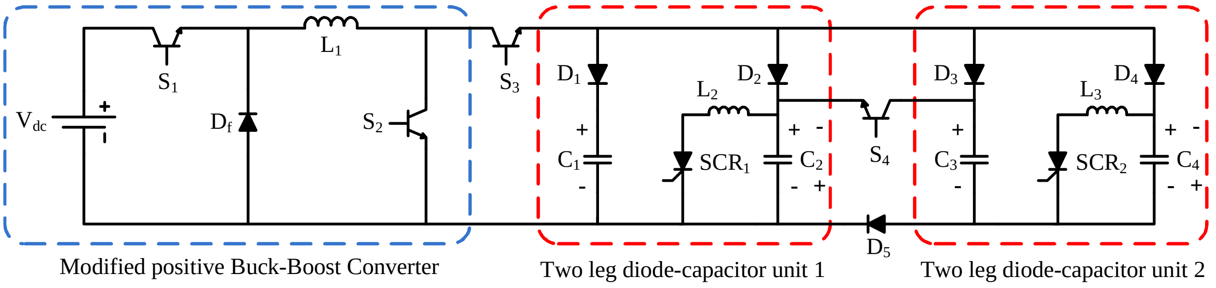

Fig. 3. Circuit diagram of the proposed topology

The stored energy and current level in the inductor can be controlled based on the duty cycles of the switches S_1 and S_2. According to (1), the voltage across the inductor is the input voltage and the time to charge the inductor at a desired current level, I_{max} can be extracted according to (2). The ultimate inductor energy can be calculated as (3).

$$V_{DC} = V_{L_1} = L_1 \cdot \frac{dI_{L_1}}{dt} \tag{1}$$

$$\Delta t_L = L_1 \cdot \frac{I_{max}}{V_{DC}} \tag{2}$$

$$E_{L_1} = \frac{1}{2} L_1 \cdot I_{max}^2 \tag{3}$$

2), Capacitors Charging Mode

In the second mode demonstrated in Fig.4.b, S_1 and S_2 are turned off and S_3 is turned on simultaneously in order to deliver the stored energy, the inductor current, into the capacitors and exchange it from the current to the voltage form.

D_1, D_2, D_3, D_4 and D_5 conduct the inductor current and charge the capacitors C_1, C_2, C_3 and C_4 at a desired voltage level with positive polarity. In this switching state, the buck-boost freewheeling diode, D_f, conducts the current to creates a current loop. Assuming the voltage drop across the diodes is not significant, and the equivalent capacitance of all four capacitors is C_{eq}, the relation of exchanged energy between the inductor and the capacitors is given in (5). If the stored energy in the inductor is entirely delivered to the capacitors, the ultimate voltage of capacitors which can be inferred from this equation will be expressed as (6).

$$C_{eq} = C_1 + C_2 + C_3 + C_4 \tag{4}$$

$$\frac{1}{2} L_1 \cdot \left(I_{L_1}(t_1)^2 - I_{L_1}(t_2)^2\right) = \frac{1}{2} C_{eq} \cdot V_C^2 \tag{5}$$

$$V_{C_{1,2,3,4}} = I_{L_1} \cdot \sqrt{\frac{L_1}{C_{eq}}} \tag{6}$$

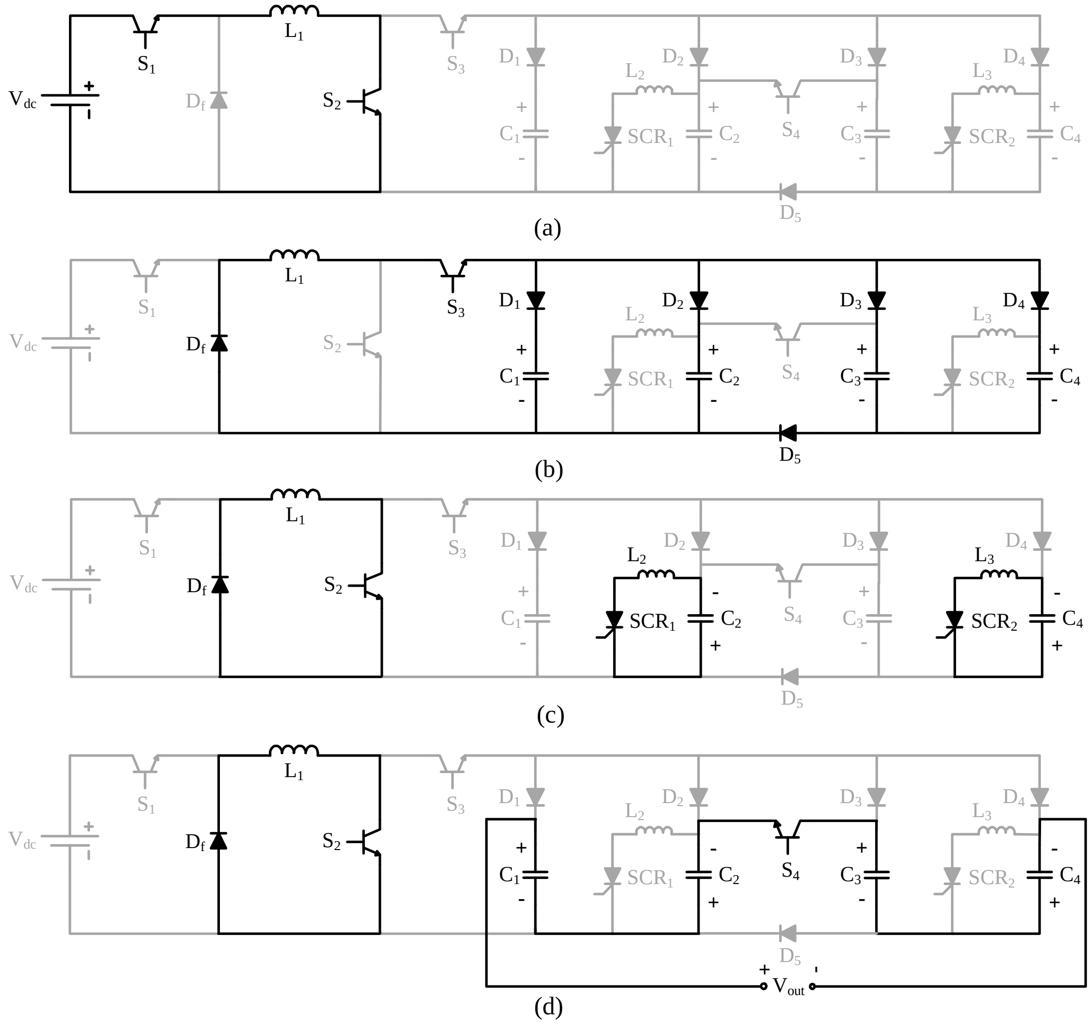

Fig. 4. Switching states of the proposed Marx generator

On the other hand, if the inductor current supposed to be constant (a large inductor is used) to provide a permanent current source for a repetitively operated pulsed power generator, the voltage across the capacitors can be calculated as follows.

$$I_{C_{eq}} = I_{L_1} = C_{eq} \cdot \frac{dV_{C_{eq}}}{dt} \quad (7)$$

$$V_{C_{max}} = I_{L_1} \cdot \frac{\Delta t_C}{C_{eq}} \quad (8)$$

Where Δt_C is a time interval to charge the capacitors at $V_{C_{max}}$.

3), Commutation Mode

In the third switching state, S_2 and S_3 are turned on and off, respectively. It is expected that the inductor has not been fully discharged during the second mode (continuous conduction mode) and its current needs to be circulated in a circuit. Therefore S_2 is turned on to circulate the remained current through D_f. On the other hand S_3 is turned off to separate the proposed topology from the buck-boost converter. If the inductor current needs to be increased for either keeping the inductor current continuous at a specific level or charging the inductor for the next switching cycle in nonrepetitive applications, S_1 can be turned on.

The next step is to change the polarity of the second (and its multiples) capacitor voltages. In this switching mode, the SCRs are turned on in order to change the voltage polarity across C_2 and C_4. A resonance happens between C_2 (C_4) and L_2 (L_3) in which the stored energy in the capacitor is delivered to the small inductor until capacitor voltage becomes zero. At this moment the inductor current is reached to its peak value and the current recharge the capacitor with opposite polarity as shown in Fig.4.c. The energy exchange between the inductive and capacitive elements of the proposed circuit is the inherent characteristics of these passive components and it is the key factor in the commutation circuits. The negative voltage across S_4 is almost two times the capacitor voltage which should be stood by the switch.

4), Pulse Generation Mode

Eventually in the last switching state the capacitors are connected in series by turning on the switch S_4. This switching mode commences when the voltage polarity of C_2 and C_4 are changed and both SCR_1 and SCR_2 become off. By turning on the switch S_4, a summation of the capacitor voltages appears across the output of the pulsed power generator. In this switching state, the inverse voltage across D_5 is almost two times the capacitor voltages which should be handled by the diode. The relevant power circuit is appeared in Fig.4.d.

C. Control Strategy

The control simplicity is an advantage of Marx modulators which is almost kept in this configuration. Despite of two simple switching states in the conventional Marx generator, this topology has four switching steps in each pulse supplying cycle. These operation modes are required due to the design attributes of this power supply. The gate signals for the power switches are generated with respect to these switching modes. In the inductor charging mode, S_1 and S_2 are switched on in order to charge the inductor. The duty cycle of S_1 and S_2 are determined through the level of inductor current based on the required stored energy in the inductor. A complimentary gate signal is used for S_3 to switch it on and off, therefore S_3 is off during this mode as well as S_4 and SCRs. In the next switching state, the capacitors charging mode, S_1 & S_2 are switched off while the inductor become charged up to a certain level. S_3 is switched on simultaneously in order to conduct the inductor current and let it charges the capacitors. On the other hand S_3 is switched off when the inductor current become less than a definite level and inductor needs to be charged for the next supplying cycle. As can be seen the gate signals for S_1, S_2 & S_3 are determined based on the inductor current. In the commutation mode, the semiconductor switches in the resonant circuits, $SCR_{1\&2}$ are turned on to inverse the voltage polarities across the relevant capacitors. The switching signals for the SCRs are determined based on the capacitors voltage. A positive and a negative voltage levels are considered to allocate the switching moments. S_2 and S_3 are on and off respectively in this mode while S_1 can be either on or off with respect to the application of topology. S_4 which was off during all former three states, is switched on in the pulse generation mode considering the second (and its multiples) capacitor voltages. Once these capacitors become fully recharged with negative polarity, the switching signal will be sent to the S_4 in order to turn it on and connect the diode-capacitor units. S_4 will be switched off after pulse imposing across the load which leads to the capacitors discharge. Therefore the turn off time for S_4 can also be specified by monitoring the discussed capacitors voltage. The above logic procedure indicates that the control mechanism of the proposed topology can be designed and implemented by sampling from two circuit parameters, the input inductor's current and the second capacitor's voltage. This makes the control strategy simple and effective. The gate drive waveforms of all utilized switches for the topology in a single pulse generation cycle are shown in Fig. 5.

III. SIMULATION RESULTS

The simulation results of the proposed converter are revealed in Fig.6. The inductors currents and the capacitors voltages can be divided into different time frames according to the switching states. The first time interval (0 until 0.5 us) is related to the charging state of the inductor up to 100 A.

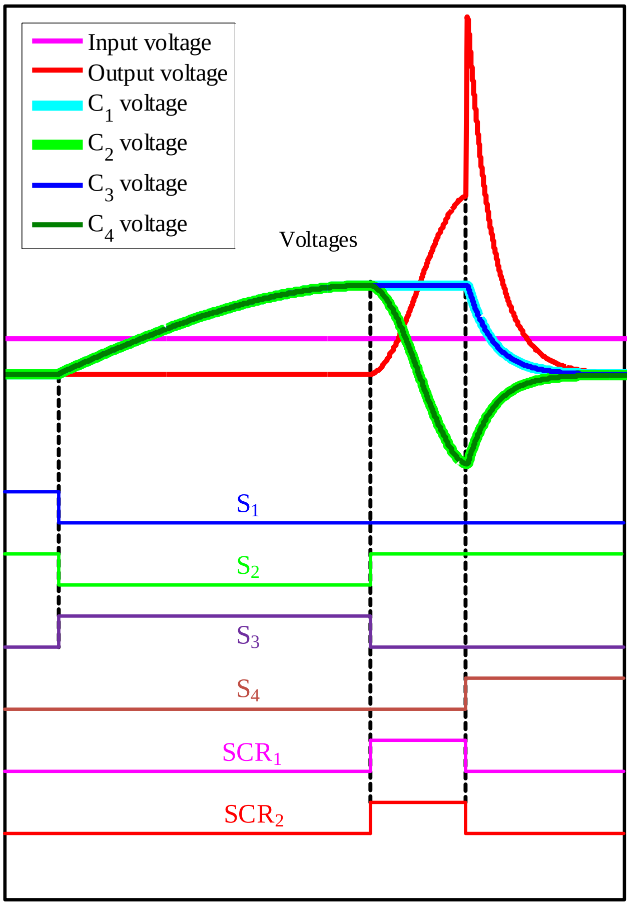

Fig. 5. The capacitors voltages and the gate drive waveforms of the converter

The next time interval (from 0.5 us to 0.8 us) is related to the charging state of the capacitors based on the second switching mode. In this mode the inductor current circulates through all four capacitors and charges them up to 500 volts. The inductor current falls to less than 5 Amps in this switching mode and will be kept in this level.

As can be seen in Fig.6.b, the voltage polarity of C_2 and C_4 are getting inverse between 0.8 us to 0.9 us due to the oscillations between passive components of the commutation circuits. The inductors currents are demonstrated in Fig.6.a as well. Then all four capacitors are connected together in series at 0.9 us by turning on the switch S_4 to generate a high voltage at the output of the converter which is almost four times each capacitor voltage. To investigate the circuit behavior while supplying the load, a 10Ω resistor is connected to the output of the converter. As anticipated, the output voltage is dropped in accompany with all capacitors discharging mode which is illustrated in Fig.6.b.

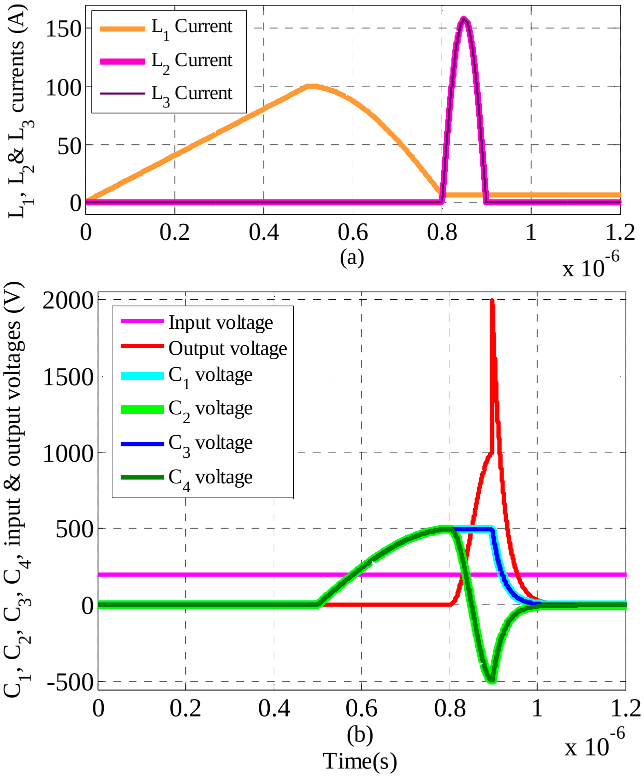

Fig. 6. Simulation results for the proposed converter

IV. THE TOPOLOGIES FEATURES AND THE COMPONENT DISCUSSION

Like all other configurations, the proposed topology has its advantages and drawbacks. There are number of issues which should be considered in the design process. First, the capacitors size should be compatible with the inductors sizes in the resonant circuits, in order to prevent the inrush currents. Since the oscillation duration in the resonant phenomena is defined with respect to the capacitor and the inductor sizes, according to (9), small components are preferred to reduce the energy exchange period and give the flexibility of generating pulsed powers with higher repetition. The passive components of the resonant circuits are determined in micro or nano ranges with respect to the energy, demanded by the load. To control the current flow in the commutation circuits, the capacitors are selected smaller than the inductors. As a result no damping element is required for the resonant circuits.

$$f_r = \frac{1}{2\pi\sqrt{L \cdot C}} \tag{9}$$

The number of stages and consequently the number of capacitors are assigned based on the load’s demand (voltage level) whereas the capacitor sizes are determined based on the required energy. On the other hand the stored energy in the input inductor should be sufficient for charging capacitors up to the certain level. Therefore, a balance between the inductor size and its current level is desired to give the required energy. Since, the inductor charging time affects the repetition capability of pulse generation, smaller inductor is preferred in this regard in order to minimize the inductor charging time.

The attributes of modeled circuit in this simulation have been presented in Table I.

TABLE I
THE SPECIFICATIONS OF SIMULATED MODEL

V_{in}	L_1	L_2	L_3	C_i	R_{1Load}	R_{2Load}
200V	1uH	100nH	100nH	10nF	1MΩ	10Ω

Second, the Collector-Emitter voltage, V_{CE}, of power switches should be in an appropriate range to handle the voltage across the switch. Each SCR should tolerate the voltage across related capacitor. Although D_5 blocks the circuit of C_2, S_4 and C_3, as shown in Fig. 7, S_4 is anticipated to stand against double capacitors voltages. The diodes, $D_{1\&2\&3\&4}$, also should be able to block the capacitor voltage.

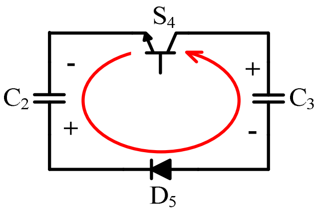

Fig. 7. The switch and the diode connecting diode-capacitor units compose circuits.

Although the market available technology always influences the equipment skills and hinder the application of it, the proposed topology can perform quite properly in comparison with former technologies considering these restrictions. In comparison with conventional Marx generator, assuming the generators supposed to generate a voltage ten times the input voltage. In this case, a ten stage conventional Marx generator is needed which is associating ten power switches, ten capacitors, and twenty power diodes. As already shown, a two stage resonant Marx generator can satisfy the mission with utilizing four power switches, two slow switches, five power diodes, and four capacitors. The point is this reduction in the number of utilized components will be more considerable when a higher voltage level supposed to be generated. Besides employing less active power elements such as semiconductor switches and diodes, the switching and conduction power loss will be markedly reduced. Furthermore, this topology has the flexibility of increasing the generated voltage level. By adjusting the inductor current, the stored energy in the inductor can be controlled and the level of voltage in the capacitors can be either boosted or decreased.

V. CONCLUSIONS

A new family of Marx generator is proposed in this paper based on parallel connection of diode-capacitor units and resonant circuits. This converter aims to generate high voltage with a topology composes of a combination of fast and slow switches. On the other hand, this converter is able to generate a flexible high voltage level at the output of the converter with a definite number of capacitors. A positive buck-boost converter delivers the energy to the diode-capacitor units which are connected together through a fast switch. Resonant circuits are used to change the voltage polarity of the second (and its multiple) capacitors. This topology generates high voltage with less number of components compare to the Marx generator. The simulation results verify the proposed topology and control in satisfaction of all expected functions.

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