A New Family of Marx Generators Based on Commutation Circuits

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ABSTRACT
This paper presents a novel topology for the generation of high voltage pulses that uses both slow and fast solid-state power switches. This topology includes diode-capacitor units in parallel with commutation circuits connected to a positive buck-boost converter. This enables the generation of a range of high output voltages with a given number of capacitors. The advantages of this topology are the use of slow switches and a reduced number of diodes in comparison with conventional Marx generator. Simulations performed for single and repetitive pulse generation and experimental tests of a prototype hardware verify the proposed topology.

Index Terms — Pulsed power, Marx generator, high voltage, resonant converter, positive buck boost converter, commutation.

1 INTRODUCTION

HIGH voltage power supplies are required for a wide and increasing range of applications; and the demand for more flexible and efficient ones is in a fast growing trend. Pulsed power is an application that frequently demands both a high voltage stress (dv/dt) and a high voltage magnitude. Currently, pulse generators are being developed for use in industrial, environmental, medical, and military applications. However the pulse characteristics such as rise and fall time, width, repetition rate, voltage and energy levels vary widely in different applications. Technologies presently used for pulsed power generation include Marx Generator (MG) [1], Magnetic Pulse Compressor (MPC) [2], Pulse Forming Network (PFN) [3] and Multistage Blumlein Lines (MBL) [4]. A recently introduced topology based on the buck-boost converter concept employs multi switch-capacitor units at the output and has the advantage of being more flexible and efficient for the generation of high repetitive pulsed power [5, 6].

As shown in Figure 1, the MG uses a simple topology to generate high voltage pulses. A number of capacitors are charged in parallel from a dc voltage source up to the input voltage level, and are then reconnected in series to produce a high voltage across the load. Developments in semiconductor technology saw the introduction of fast high voltage switches including Insulated Gate Bipolar Transistors (IGBT) and Metal–Oxide–Semiconductor Field–Effect Transistors (MOSFET). These compact and efficient solid-state devices have replaced bulky, heavy, costly and inefficient gas and magnetic switching devices (such as the spark gap and the hydrogen thyratron) used for many years [7-9]. Exploitation of solid-state technology in the high-voltage generation provides the flexibility of generating pulses for various load conditions [9, 10]. Although their voltages ratings do not exceed a few hundred volts, several MGs in the range of hundred kVs have been designed and implemented using these switches [11, 12]. Several configurations aiming to ensure the feasibility of generating pulsed power with adjustable features have been proposed so far. All solid-state MG for generating bipolar pulses [13], high repetitive pulses [9, 14] and pulses with flexible pattern [15] have also been designed with different configurations of semiconductor switches. Although MGs are in use in a wide range of applications, there are still design and control techniques that can be adopted to improve their performance in terms of both efficiency and flexibility.

Figure 1. A conventional Marx generator.
Resonant phenomenon is used in power electronics to minimize switching losses and the concept of resonant converters has been developed for this purpose. Switching at the instant at which the conducting current passes through the zero level, keeps the switching losses in the power switches to a minimum [16]. In addition, the use of a commutation circuit is another useful technique that utilizes resonant phenomenon to reverse the polarity of a capacitor voltage. These techniques are used in the proposed topology to produce pulsed power.

2 CONFIGURATION AND ANALYSES

2.1 TOPOLOGY

The topology proposed in this paper as an MG, comprises a positive buck-boost converter that is used as a current source and connected to a number of parallel-connected diode-capacitor units, as shown in Figure 2. The converter charges the capacitors to a specified voltage and the commutation technique is employed to connect them in series and to produce the required high voltage at the output of the system.

As can be seen in Figure 2, a full-bridge diode rectifier connected to the grid provides a dc voltage for the remainder of the system. The single pulse applications usually demand high amount of accumulated energy in each shot, whereas less instantaneous energy is demanded by the repetitive pulse applications. Although a repetitively operated generator with a moderate peak power needs less primary stored energy than a single-shot generator [17, 18], the input source should be able to provide a continuous power supply for the repetitively operated generator. A three-phase rectifier can be utilized for this purpose in order to provide primary uninterruptable energy supply from the grid.

A positive buck-boost converter is considered in the next stage to provide the flexibility of boosting the voltage to any desired level. This converter is connected to the proposed Marx topology through a power switch that disconnects the Marx topology from the rest of the circuit after charging the capacitors.

A detailed circuit diagram of the above topology, including the diode-capacitor units is shown in Figure 3. As will be seen, the second and its multiple legs contain a resonant circuit that includes an inductor and a slow semiconductor switch, Silicon-Controlled Rectifier (SCR). The small inductor is connected to the capacitor through the SCR to change the polarity of the capacitor voltage. Such energy exchange process, known as commutation [19], makes series connection of the capacitors feasible. In the proposed method, the polarity of the capacitor voltages is alternately inverted and subsequently a connection between the units using a fast switch, $S_4$ is sufficient to provide series connection of the capacitors. The number of units can readily be increased and a higher voltage can be produced at the output of the system.

2.2 SWITCHING MODES

The switching modes of the proposed converter for single pulse generation consist of the four states which are shown in Figure 4.

2.2.1 FIRST MODE: INDUCTOR CHARGING MODE

In the first state, shown in Figure 4a, the main inductor, $L_1$, located at the input of the converter is charged through $S_1$ and $S_2$, while $S_3$ ensures that the rest of the circuit is disconnected. The charged inductor acts as a current source for the rest of topology in the subsequent modes. The current level defining the energy stored in the inductor can be controlled based on the duty cycles of the switches $S_1$ and $S_2$.

Let us assume that all the semiconductor devices including IGBTs, SCRs and diodes are ideal components. Then the voltage drop across each of them is zero when it conducts. According to (1), the voltage across the inductor is the input voltage and the time to charge the inductor to a desired current level, $i_{max}$, and the ultimate inductor energy are given in (2), and (3) respectively.
In the second mode, shown in Figure 4b, S1 and S2 are turned off and S3 is turned on simultaneously to deliver the energy stored in the inductor into the capacitors, and to convert it from electromagnetic to electrostatic form.

Diodes, D1, D2, D4, and D3 conduct the inductor current and charge the capacitors C1, C2, C3, and C4 to the desired voltage level with positive polarity. In this state, the buck-boost freewheeling diode, D5, conducts the current to create a current loop. Assuming the voltage drop across the diodes is negligible, and the equivalent capacitance of the four capacitors is $C_{eq}$, the relation of exchanged energy between the inductor and the capacitors is as given in (5). Instants $t_1$ and $t_2$ respectively are the instants at which the inductor current is fully charged or partly discharged and can be realized by turning off and on the gate signals for S3. If the energy stored in the inductor is completely delivered to the capacitors ($i_L(t_1) = 0$), the final voltage of the capacitors can be expressed as in (6).

\[ V_{dc} = V_i = L_1 \frac{di_L}{dt} \]  
\[ \Delta t_L = L_1 \frac{i_{max}}{V_{dc}} \]  
\[ E_{eq} = \frac{1}{2} L_1 \cdot (i_L(t_1))^2 - \frac{1}{2} L_1 \cdot (i_L(t_2))^2 = \frac{1}{2} C_{eq} \cdot V_C^2 \]  
\[ C_{eq} = C_1 + C_2 + C_3 + C_4 \]

Alternatively, if the inductor current, $i_L$, is assumed constant (i.e., a large inductor is used) to provide a permanent current source for a repetitively operated generator, the voltage across the capacitors can be calculated as follows.

\[ i_{C} = i_L = \frac{dV_{Ceq}}{dt} \]  
\[ V_{C_{eq}} = i_L \frac{\Delta t_C}{C_{eq}} \]

where $\Delta t_C$ is the time required to charge the capacitors to $V_{C_{eq}}$.

### 2.2.3 THIRD MODE: COMMUTATION MODE

As shown in Figure 4c, in the third switching state, S2 and S3 are respectively turned on and off. It is expected that for single shot generator, the inductor will not have been fully discharged during the second mode (i.e. it is working in a continuous conduction mode, CCM) and its current needs to be circulated in a circuit. For a repetitively operated pulse generator, the converter performs in a CCM, and the inductor current never falls to zero. Therefore S1 is turned on to enable the remaining current to circulate through D6. Simultaneously, switch S1 is turned off to separate the proposed topology from the buck-boost converter. If the inductor current needs to be increased to either keep the inductor current continuous at a specific level in a repetitive application or to charge the inductor for the next switching cycle in a nonrepetitive application, S1 can be turned on (Figures 5a and 5b).

The next step is to change the polarity of the second (and any further) capacitor voltages. In this mode, the SCRs are turned on to change the voltage polarity across C2 and C4. Resonance occurs between C2 (C4) and L2 (L4), during which the stored energy in the capacitor is delivered to the small inductor until the capacitor voltage becomes zero. At this instant, the inductor current reaches its peak value and the current recharge the capacitor to a reversed polarity. The energy exchange between the inductor and the capacitor is an inherent characteristic of the components and is a key factor of the commutation circuits.

### Figure 5. Extra switching states of the proposed Marx generator for repetitive pulse generation.
Although it appears at first sight that the negative voltage across $S_4$ is almost twice the capacitor voltage and must be withstood by the switch in this state, the diode $D_5$ provides the necessary protection by sharing this voltage.

2.2.4 FOURTH MODE: PULSE GENERATION MODE

Eventually in the final switching state the capacitors are connected in series by turning on switch $S_5$. This mode begins when the voltage polarities of $C_2$ and $C_3$ are changed and both $SCR_1$ and $SCR_2$ are turned off. By turning on switch $S_5$, the summation of the capacitor voltages appears across the output of the generator. In the beginning of this state, the inverse voltage across $D_5$ is almost twice the capacitor voltage which should be handled by the diode. The relevant power circuit is shown in Figure 4d.

2.3 CONTROL STRATEGY

Two separate control algorithms (switching procedures) are adopted, one for single pulse generation and the other for repetitive pulse generation. The control simplicity is an advantage of MGs, and is almost maintained in this configuration. Instead of the two simple switching states in the conventional MG, this topology has four switching steps for each pulse generation cycle while acting as a single pulse generator. These operation modes are necessary due to the design requirements of the MG, and the gate signals for the power switches are generated with respect to these modes. In the inductor charging mode, $S_1$ and $S_2$ are switched on to charge the inductor and the duty cycles of $S_1$ and $S_2$ are determined through the level of inductor current based on the required storage of energy in the inductor. A complimentary gate signal is used to trigger $S_1$ on and off, and therefore $S_3$ is off during this mode as well as $S_4$ and the SCRs. In the next switching state, the capacitor charging mode, $S_1$ and $S_2$ are switched off once the inductor is charged up to a certain level. $S_1$ is switched on simultaneously to conduct the inductor current and so charge the capacitors. In addition, $S_1$ is switched off when the inductor current fall below a defined level and the inductor needs to be charged for the next supplying cycle. At this point, $S_1$ and $S_2$ are turned on to again charge the inductor. As can be seen in Figure 6, the gate signals for $S_1$, $S_2$ and $S_3$ are determined by the inductor current. In the commutation mode, the switches in the commutation circuits, $SCR_1$ and $SCR_2$ are turned on to reverse the voltage polarities across the relevant capacitors ($C_2$ and $C_3$). The switching signals of the SCRs are determined by the capacitors voltage. $S_2$ and $S_3$ are switched on and off respectively in this mode, whilst $S_1$ can be either on or off. Once these capacitors are fully recharged at a negative polarity, the switching signal is sent to $S_4$ to turn it on and to connect the diode-capacitor units. $S_4$ will be switched off after the generated pulse is applied to the load and the capacitors are discharged. The turn off time for $S_4$ can therefore also be specified by monitoring the discussed capacitor voltage. The above logic procedure indicates that the control mechanism of the proposed topology can be designed and implemented by sampling two circuit parameters, the current of the input inductor and the voltage of the second capacitor. This makes the control strategy both simple and effective.

The gate drive waveforms of all the switches used for the topology of a single pulse generation in a cycle are shown in Figure 6.

The control algorithm is more complicated for repetitive pulse generation due to the greater number of safety issues. The flowchart in Figure 7 shows how the decisions are made for the topology to supply a load with repetitive pulses. To charge the capacitors alternatively at a high repetition rate, the input inductor ($L_1$) current should be kept relatively constant at a specific value. A band is therefore defined to switch $S_1$ and $S_2$ on and off and to keep the inductor charged steadily. $S_1$ is turned on and off with respect to both the inductor current and the capacitor voltages. $S_4$, $SCR_1$ and $SCR_2$ are turned on and off as in the former strategy. The repetitive control strategy contains two switching modes more than the single shot strategy.

### 3 SIMULATION RESULTS

Simulation results for the proposed MG with both single and repetitive pulse generations are shown in Figure 8 and Figure 9. The circuit parameters used in the simulations are recorded in Table 1.

Table 1. The specifications of simulated models.

<table>
<thead>
<tr>
<th></th>
<th>$V_{in}$</th>
<th>$I_1$</th>
<th>$L_2$</th>
<th>$L_3$</th>
<th>$C_1$</th>
<th>$R_{Load}$</th>
<th>$R_{Load}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>200 V</td>
<td>1 $\mu$H</td>
<td>100 nH</td>
<td>100 nH</td>
<td>10 nF</td>
<td>1 M $\Omega$</td>
<td>10 $\Omega$</td>
</tr>
<tr>
<td>Repetitive</td>
<td>200 V</td>
<td>433 $\mu$H</td>
<td>1 $\mu$H</td>
<td>1 $\mu$H</td>
<td>10 nF</td>
<td>1 M $\Omega$</td>
<td>10 $\Omega$</td>
</tr>
</tbody>
</table>
The inductor currents and the capacitor voltages in Figure 8 for the single shot MG can be divided into different time frames according to the switching states. The first time interval (0 to 0.5 $\mu$s) is for the charging state of the inductor up to 100 A. The next time interval (from 0.5 to 0.8 $\mu$s) is for the charging state of the capacitors in the second switching mode. In this mode the inductor current circulates through all four capacitors and charges them to 500 V. The inductor current falls to less than 5 A in this switching mode and is maintained in this level.

As can be seen in Figure 8b, the voltage polarities of $C_2$ and $C_4$ are reversed between 0.8 to 0.9 $\mu$s, due to the oscillations between the passive components of the commutation circuits. The inductor currents are also shown in Figure 8a. All four capacitors are connected together in series at 0.9 $\mu$s by turning on the switch $S_4$, to generate a voltage at the output of the MG almost four times each capacitor voltage. To investigate the circuit behavior when supplying a load, a 10$\Omega$ resistor is connected to the output of the MG.

**Figure 7.** The control flowchart for a modulator with the repetitive pulse generation function.

**Figure 8.** Simulation results for the proposed converter (single pulse).

**Figure 9.** Simulation results for the proposed converter (repetitive pulses).
As anticipated, the output voltage falls as all the capacitors lose charge and therefore voltage, as illustrated in Figure 8b.

In addition to the change in the component sizes evident in Table I, the current level in the input inductor, $L_1$, and the switching modes sequence are also changed in order to adjust the MG for a high repetitive pulse generation. The key issue in this case is the input inductor size, which should be larger than for single pulse generation. The higher input voltage can provide the inductor with faster charging and increase the modulators pulse generation repetition. As shown in Figure 9a, the inductor current fluctuations between 20 A and 19.5 A are due to charging by the input voltage and discharging through the capacitors.

The voltage across and the current through all switches are given in Figure 10. In this case, medium voltage rate IGBTs can be used as $S_1$, $S_2$, $S_3$ and $S_4$. Simple SCRs can also be utilized to withstand against the normal range of voltages. All the fast switches are at a reasonable current level except for $S_4$. In this case, the current peak is 200 A, although it can be even higher for an MG with more capacitive units. Although the current level in the supplying mode is critical for solid-state power switches, semiconductor devices are available which can handle this level of current, specifically when it flows in the form of pulses. Normally, when dealing with pulsed currents, an operating level higher than the rated dc level is possible for solid-state components. The analyses of the voltage and the current of switches in this model reveal that with a proper selection of components, the proposed topology can accomplish all the anticipated functions.

### 4 EXPERIMENTAL VERIFICATION

A simple four-stage MG is implemented to study the proposed configuration practically. SEMIKRON IGBTs and SCRs are used to arrange the hardware. Skyper 32-pro gate drives which are compatible with these switches are used to provide the gate drive signals needed for triggering the switches. NEC 32-bit 64MHz V850/IG3 micro-controller is used to control the gate drives. The specifications of the circuit are listed in Table 2. The experimental set up is shown in Figure 11.

<table>
<thead>
<tr>
<th>$V_{in}$</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$L_3$</th>
<th>$C_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 V</td>
<td>433 µH</td>
<td>220 µH</td>
<td>220 µH</td>
<td>10 nF</td>
</tr>
</tbody>
</table>

The experimental results obtained are shown in Figures 12a and 12b. The capacitor and the output voltages and the input inductor current are shown in Figure 12a. The operation modes, including the inductor and capacitors charging modes, followed by the commutation and the pulse generation modes can be distinguished in this figure. The summation of voltages across $C_1$ and $C_n$ ($n=4$ in this case) appears across the load during third (commutation) mode. The rest of voltages ($V_{C2}+...+V_{C(n-1)}$) are added to this level by triggering on $S_4$ (and its multiple switches) at the fourth (pulse generation) mode. The energy exchange process in the commutation circuits is illustrated in Figure 12b, through depicting the involved capacitor ($C_2$ and $C_4$) and inductor ($L_2$ and $L_3$) voltage and current waveforms.

![Figure 10. The switches voltages and currents.](image1)

![Figure 11. The experimental set up.](image2)
5 THE DESIGN FEATURES AND THE COMPONENT DISCUSSION

There are a number of issues which should be considered in the design process. Firstly, the inductor sizes should be compatible with the capacitor sizes in the commutation circuits in order to prevent inrush currents. Since the duration of oscillations in the resonant phenomena is defined with respect to the capacitor and the inductor sizes, according to equation (9), small components are preferred to reduce the energy exchange period and to give the flexibility of generating pulsed power with a higher repetition rate. Therefore, the inductors are selected sufficiently large to control the current peaks.

\[ f_r = \frac{1}{2\pi\sqrt{L \cdot C}} \]  

The number of stages, and consequently, the number of capacitors are determined by the voltage required by the load, whereas the capacitor sizes are determined by the required energy. On the other hand, the stored energy in the input inductor must be sufficient to charge the capacitors to a defined level. A balance between the inductor size and its current level is necessary to give the required energy.

Electromagnetic interfere (EMI) is the other issue which should be taken into consideration when using switching equipment that trigger devices in a high frequency. The electromagnetic fields which are generated due to this high repetition rate and switching transients cause interference that may influence other equipment like optical receivers. To prevent such incidents, all the current loops in the printed circuit board (PCB) should be laid out with minimum stray inductance. Using planar busbar configuration is an effective method to minimize the magnetic fields and the radiated noises in the hardware set up [20].

The collector-emitter voltage, \( V_{CE} \), of power switches should be adequate to handle the voltage across the switch. Each SCR should withstand the voltage across the related capacitor. \( D_5 \) blocks the circuit of \( C_2, S_4 \), and \( C_3 \), as shown in Figure 13. Although the voltage sharing across \( S_4 \) and \( D_5 \) in the third mode is not predictable, due to the different characteristics of these components, simulation results in Figure 10 indicate that they share the voltages across \( C_2 \) and \( C_3 \) almost equally. The summation of \( C_2 \) and \( C_3 \) voltages is located across \( D_5 \) once \( S_4 \) is triggered on at the beginning of fourth mode. Therefore \( D_5 \) is required to withstand twice the capacitor voltage, in order to block the circuit in the fourth mode, whereas \( S_4 \) rating is equivalent to the charge across one capacitor. Diodes, \( D_1 \), \( D_2 \), \( D_3 \) and \( D_4 \), also should be able to block a capacitor voltage.

The significant achievement of this design is the substitution of fast IGBTs with slow SCRs. Although, SCRs are slower devices, they require fewer driving modules rather than IGBTs. In addition, fewer diodes are used in this design. This leads to reductions in the cost, losses, volume, weight, and system intricacy. To generate an output voltage that is ten times the input voltage, the proposed topology requires far fewer modules and components than a conventional MG. A conventional MG will involve ten fast power switches, and twenty power diodes, whereas, a ten-stage proposed MG will need only four fast power switches, five slow switches, and fourteen power diodes. Besides employing fewer active power elements (such as solid-state switches and diodes), the switching and conduction power losses will be markedly reduced due to having fewer components in the discharging path. Furthermore, the whole converter has the flexibility to increase the generated voltage level through a lower input voltage. By adjusting the inductor current level, the stored energy in the inductor can be controlled and the level of voltage in the capacitors can be either boosted or decreased.

![Figure 13](image_url)

**Figure 13.** The switch and the diode which connect diode-capacitor units compose a circuit.
4 CONCLUSION

A new family of Marx generator is proposed in this paper based on the parallel connection of diode-capacitor units and commutation circuits. This converter aims to generate high voltage with a topology and control components than a conventional MG. The simulation and the experimental results verify the proposed topology and control in satisfaction of all expected functions.

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