A Novel Marx Generator Topology Design for Low Source Impedance

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Abstract

The typical Marx generator designs employ a single stage switch, which usually results in a high source inductance, and ultimately high source impedance, relegating the Marx generator to the role of a high voltage pulse-charging source. A low impedance Marx generator may be used to directly source low impedance loads, such as High Power Microwave loads. Applied Physical Electronics, L.C. (APELC) has developed a new Marx topology based on distributed stage capacitance and parallel stage switches that has been demonstrated to reduce the generator's series inductance. The erected Marx voltage is 1 MV, with a source impedance of 18 Ω. This paper discusses the Marx topology, with demonstrations made to illustrate the topology's effectiveness for the APELC MG20-24C-2000PF

I. INTRODUCTION

Typical High Power Microwave (HPM) systems employ a Marx generator in a Pulse Forming Line configuration to source low impedance loads such as the Magnetically Insulated Line Oscillator (MILO) and the virtual cathode (vircator). The Marx generator pulse-charges the PFL, which is designed to quickly transfer energy into the impedance matched load with a specified pulse length. To maximize the charge voltage on the PFL, the Marx generator is usually has an energy store of several times the storage capacity of the PFL. The Marx and PFL together comprise a large capacitive energy store with excessive volume and weight for use beyond laboratory operation.

Further complicating HPM systems is the use of oils, deionized water and hazardous gases, such as sulfurhexaflouride (SF_6) to enable HV operation. Transformer oil is used for insulating the Marx generator, SF_6 is often used for insulating components, as well as for gas mixtures for the spark gap switches, and de-ionized water is often employed as the medium in the PFL. Because of the extra hardware and ancillary systems, a more ideal configuration would employ a low impedance Marx generator designed to directly drive the HPM load; furthermore, the Marx generator would not use oils or hazardous gases.

APELC has developed a prototype Marx generator that is specifically designed to directly drive HPM loads. The generator introduces a novel circuit topology based on distributed capacitance and parallel switching that leads to coaxial-like conduction, and ultimately, a low source impedance.

II. Background and Design

A. Traditional Marx Generator Design

Traditional Marx generator designs are based on a single switch per Marx stage and may include one to two capacitors for energy storage. Figure 1 illustrates a simple implementation of a Marx generator designed for HPM use. Two high energy plastic capacitors and an encased spark gap make up a single stage. The Marx generator is then usually contained in a large metal box, which is filled with transformer oil, to insulate the capacitors from the ground plane.

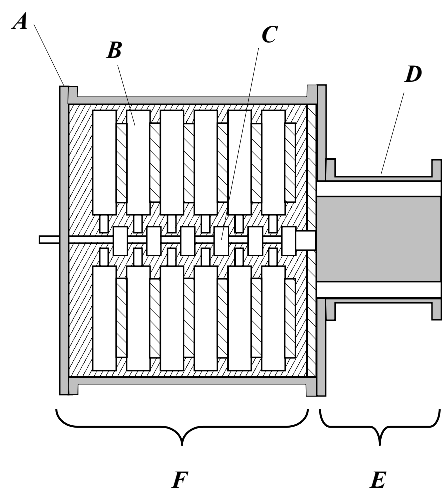

Figure 1. A traditional Marx design for HPM systems. Marx generator (***A***), Maxwell capacitor (***B***), Maxwell spark gap switches (***C***), PFL (***D***), Energy related to pulse length (***E***), 10x energy stored in PFL (***F***).

B. APELC's Novel Marx Generator Topology

The APELC topology for this paper represents evolutionary advancement beyond traditional Marx generator designs. As shown in Figure 2, the stage capacitance is distributed into a number of capacitors and the stage switch is divided into parallel paths, with each switch being located in close proximity of the ground plane. In the prototype construction, twenty-two door-

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knob capacitors and eight parallel spark gap switches were used. The Marx stages are electrically separated with an ABS plastic layer (Acrylonitrile Butadiene Styrene). The stage capacitors are fixed to the ABS spacers via a brass interconnection tab, which is held into place by brass electrodes. The completed stages are vertically stacked bottom (input) to top (output), with the trigger section mounted directly beneath the first stage and just above the input plate. The Marx circuit is then encased in an aluminum tube that is electrically insulated with an epoxy liner.

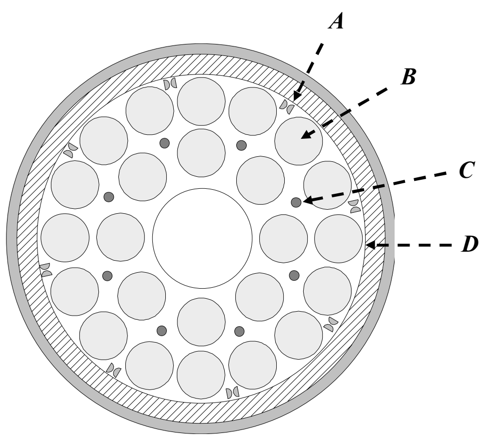

Figure 2. The APELC Marx generator MG20-24C-2000PF stage topology. Parallel spark gaps (***A***), door knob capacitors (***B***), support rod (***C***), and epoxy liner (***D***).

Three components are critical to the parallel switching topology. First, the electrical propagation time between neighboring spark gaps must be maximized, so that the closure of one spark gap does not prematurely collapse the voltage of its neighboring spark gaps. Second, each of the parallel spark gaps should be optically aligned with the previous stage's spark gap switches for pre-ionization and faster closure times. Third, the parallel switching topology must be initiated with a parallel triggering scheme.

The parallel switching scheme is illustrated in Figure 3. As is the case for traditional Marx circuits, the first spark is the trigger gap; this design employs eight parallel trigger gaps, employing the trigatron trigger method. In this construction, each gap has its own trigger circuit. Although the trigger gaps correspond to separate circuits, each shares a common *master switch*, so that the trigatrons are simultaneously excited to maximize the probability of simultaneous closure of the first Marx switches.

The topology offers a number of advantages over traditional Marx generator designs via the distributed capacitance, i.e. multiple capacitors per stage to place the stage capacitors' inductance in parallel. The distributed capacitance distributes ESR losses. Next, the parallel switching reduces the series inductance and places the parallel switches in close proximity to the ground plane to reduce streamer inductance. Parallel switches also more evenly distribute the stage circumference leads to near coaxial current conduction on the Marx housing. Parallel switching gives further advantage by reducing Joule heating on the individual spark gaps.

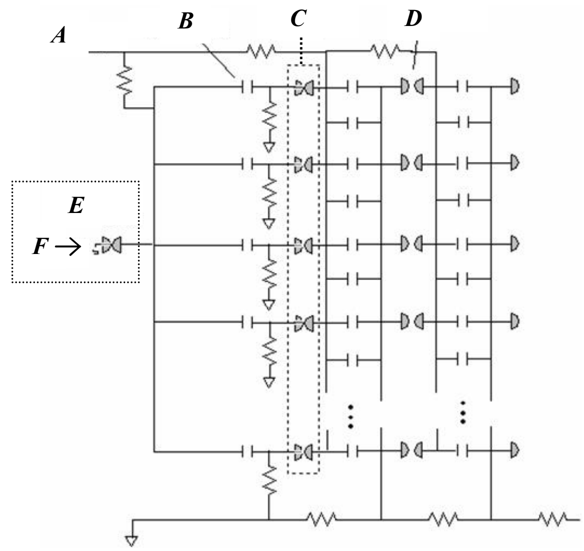

Figure 3. The trigger scheme of the APELC Marx topology. High voltage in (***A***), trigger capacitor (***B***), Parallel (stage) trigger gaps (***C***), stage capacitor (***D***), Main trigger gap (***E***), trigger in (***F***).

C. Design Specifications

The primary goal for the APELC Marx generator MG20-24C-2000PF is to provide low source impedance in order to directly drive HPM loads. In the design phase we initially targeted a load impedance of 20 Ω. MG20-24C-2000PF is designed to store 1 kJ energy store, with upgrade capability provided by the inclusion of custom conformal capacitor bodies which more effectively utilize open space visible in fig 2. The existing design exhibits a sub 10-ns voltage rise time and a 10 Hz repetition rate, with a housing volume of less than a 24 inch diameter and 72 inch length.

D. Prototype Electrical and Physical Characteristics

The electrical design characteristics of the APELC MG20-24C-2000PF are listed in Table 1. The prototype generator is designed for an erected voltage of 1 MV. For a charge voltage of 50 kV, twenty stages yield the targeted 1 MV. The generator is also designed for an approximate 1 kJ stored energy at full voltage. Using the TDK UHV-9A door-knob capacitor, a stage capacitance of 40 nF results, with an erected capacitance of 2 nF.

In order to achieve 50% voltage efficiency with a 20 Ω load, the generator must also have a matched impedance, or a series inductance of 800 nH.

E. Load Design and Diagnostics

The load assembly in fig 4 was designed for voltage diagnostics and was constructed to sustain high voltage and shock, while maintaining the ability for quick change of internal resistors in order to measure voltage characteristics at variable load impedances. Internal load

Table 1. Electrical Characteristics of the APELC Marx generator MG20-24C-2000PF.

Parameter	Description	Value	Unit
V_{open}	Open circuit voltage	1	MV
V_{ch}	Maximum charge voltage	50	kV
Z_{load}	Load impedance	20	ohm
C_{basis}	Basis capacitor	2	nF
N	Number of stages	20	-
N_{cap}	Number capacitors per stage	22	-
C_{stage}	Capacitance per stage	44	nF
C_{marx}	Erected Marx capacitance	2.2	nF
L_{marx}	Marx series inductance	712	nH
Z_{marx}	Marx impedance	18	ohm
Eff.	Voltage efficiency	52.6	%
P_{power}	Maximum peak power	12.5	GW
E_{marx}	Energy stored at maximum voltage	1.1	kJ
T_{RR}	Maximum repetition rate	10	Hz
P_{ave}	Maximum average power	11	kW

Table 2. Physical characteristics of the APELC Marx generator MG20-24C-2000PF.

Parameter	Description	Value	Unit
L	Length	60	in
D	Diameter	19	in
Wt	Weight	1000	lbs

resistors were *Kanthal* AS series high-energy carbon resistor chosen for voltage hold-off and energy capabilities. Other diagnostics included a calibrated T&M Research CVR used for monitoring the current and an uncalibrated capacitive voltage divider primarily used to observe the voltage rise time.

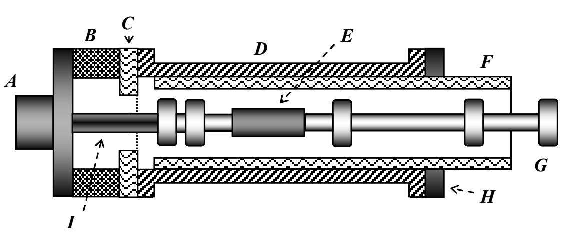

Figure 4. Load design and diagnostic tools for the APELC Marx generator MG20-24C-2000PF. T&M Research CVR (***A***), extension collar (***B***), acrylic insulator (***C***), aluminum housing (***D***), Kanthal resistor (***E***), acrylic liner (***F***), aluminum feed (***G***), capacitive voltage probe collar (***H***), internal conductor (***I***)

IV. EXPERIMENTAL RESULTS

The generator was initially tested for its impedance using a T&M Research CVR (0.009809 Ω) directly mounted to the output section of the generator, as described by Figure 4. A short-circuiting rod replaces the Kanthal AS-series resistor for this ring-down measurement. The CVR-measured waveform is shown in Figure 5.

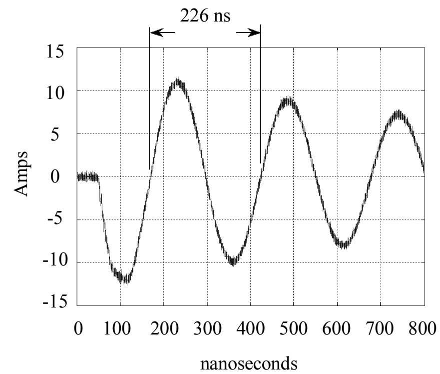

Figure 5. The CVR-measured ring-down. Ring down period τ=226 nsec. .

The resulting waveform has a characteristic frequency of approximately 4.4 MHz. The Marx inductance L_{Marx} and impedance Z_{Marx} were calculated from the ring-down frequency, erected capacitance as follows

$$L_{Marx} = \frac{1}{(2\pi f)^2 C_{erect}} = 712\,nH \quad (1)$$

$$Z_{Marx} = \sqrt{\frac{L_{Marx}}{C_{erect}}} = 18\,\Omega\cdot \quad (2)$$

Initial measurements of the generator's output were made with the load configuration of Figure 4, using a 15 Ω resistor and a charge voltage of 20 kV.

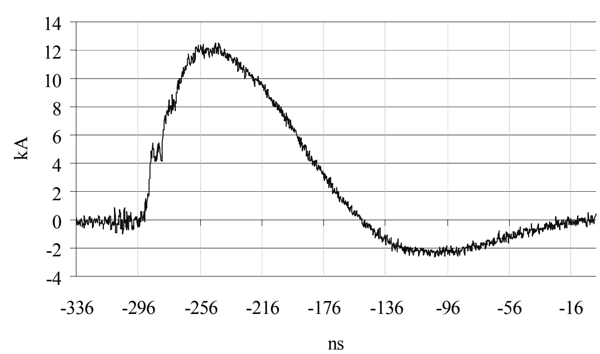

Figure 6. Output waveform with a 20 kV charge.

In figure 6, the peak current reaches 12 kA, providing additional confirmation of the 18 Ω source impedance. The pulse is characterized by a four to five nanosecond rise time for approximately 40% of the peak voltage; the pulse then slows to a rise time of approximately twenty-five nanoseconds the duration of the rising edge.

The two distinct rise times are due to the variances in the load impedance as the output pulse propagates through the load. A Time Domain Reflectometry (TDR) measurement is made using the configuration of Figure 7.

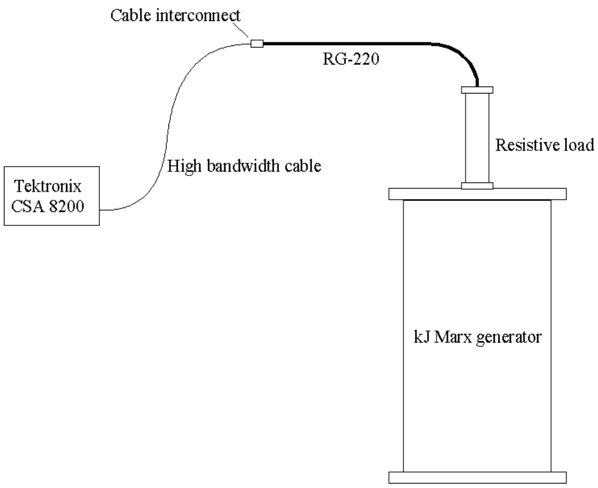

Figure 7. A TDR measurement made on the Marx load.

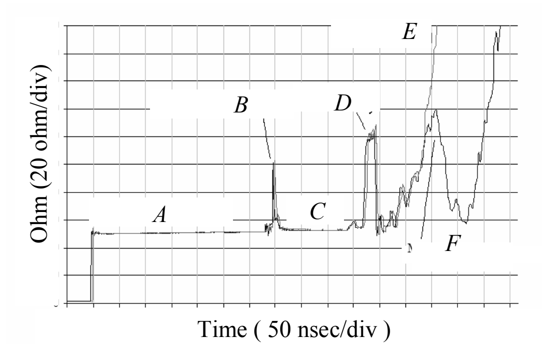

Figure 8. TDR measurement of Marx generator. Solid line. High bandwidth cable (*A*), cable interconnect (*B*), RG 220 (*C*), CVR cavity (*D*), Load removed (*E*), Marx load in place (*F*)

The resulting TDR waveforms are presented in Figure 8. As noted in the figure, two TDR waveforms are presented, (1) with the Marx as a load, and (2) with the load element removed. The cable changes and the CVR cavity are noted for clarifying the resulting waveforms.

With the "loaded" waveform, the impedance rises to the approximate 100 Ω of the resistor, before seeing the high impedance of the output section of the Marx, and then abruptly increases in impedance due to the spark gaps. We note that the aside from the resistor, the output (load) structure is coaxial in its geometry, with an approximate impedance of 120 Ω. Hence it becomes apparent that the TDR begins to experience the 120 Ω impedance, but increases in impedance due to the resistor impedance, to what appears to be an approximate output impedance of 130 – 140 Ω. Removing the load from the Marx, and measuring with the TDR, results in a rapid increase in impedance, at the point of the output section of the Marx.

To further explore the generator's change in rise time, a variety of load resistors are used in analyzing the performance of the generator. Most recent measurements have been made with a charge voltage of more than 40 kV, with the generator showing the capability of operating with a 1 Hz repetition rate (power supply limited). A sample waveform is shown in Figure 10. This waveform results from a 40 kV charge voltage into a 15 Ω load, and delivering approximately 24.4 kA in peak current.

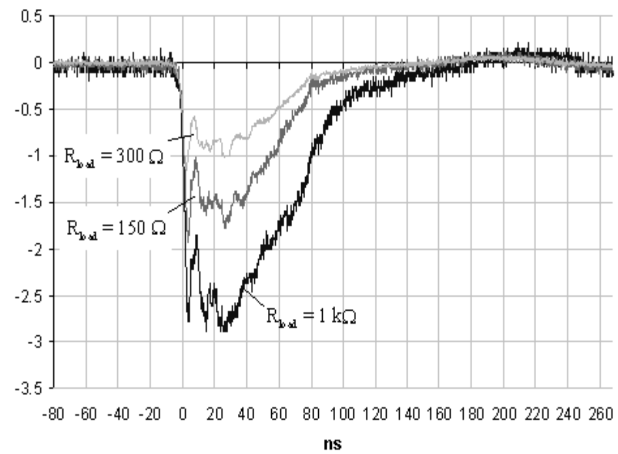

Figure 9. Output waveforms with various load resistors.

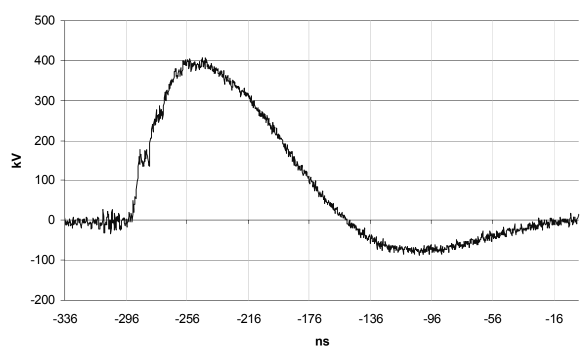

Figure 10. Output waveform with a 40 kV charge.

V. CONCLUSION

This paper has presented preliminary results of a compact MV Marx generator. The generator was initially tested for its impedance using a T&M Research Products CVR directly mounted to the output section of the generator. Measuring the frequency of the ring-down, and with the known erected capacitance, the Marx inductance was calculated to be approximately 1.19 μH, which leads to an impedance of 70 Ω).

The generator was then tested at various charge voltages and with various pressure levels. Operating at the capacitors' voltage rating, the generator delivers more than 450 kV into a 50 Ω cable load. And as the voltage was increased to 1.5 times the capacitors' rating (or 45 kV), peak voltages in excess of 800 kV were measured.

Future efforts will work to construct a more compact and more modular generator. The generator will also be fitted with inductive charging elements for faster charge cycles and higher repetition rates.