# DESIGN AND PERFORMANCE OF AN ULTRA-COMPACT 1.8-KJ, 600-KV PULSED POWER SYSTEM

**C. Nunnally[⊥], J. R. Mayes, C. W. Hatfield, J. D. Dowden**
*Applied Physical Electronics L C , PO Box 341149*
*Austin, TX, USA*

*Abstract*

A new, high-energy-density Marx generator has been developed for High Power Microwave (HPM) applications. The generator (P/N: MG30-3C-100NF) has been shown to deliver 5 GW to a 25 Ohm load with a peak pulse voltage of 300 kV. A modular close-packing geometry combined with mica-film capacitor technology results in a 1.8 kJ energy storage capacity in a 20 in. diameter x 45 in. cylindrical vessel. The compact architecture accomplishes a high energy per pulse, but also facilitates a relatively low inductance of the system which is characterized by a 90 ns voltage risetime when discharged into a matched resistive load. The system includes an EMI-hardened power electronics suite which includes a solid-state trigger generator, compact HVPS, and a digital pressure regulator. The system requires only pressurized dry air for insulation, operates on an internal prime-power battery pack and is controlled via a fiber-optic remote for ease of use on remote platforms. The system design and pulse characteristics are presented in this paper.

## I. BACKGROUND

High Power Microwave (HPM) generators such as the Virtual Cathode Oscillator (Vircator) typically require many 100s of kV to MV voltage pulses and pulse durations 100s of ns and longer to effectively radiate [1, 2]. Several pulse generator schemes have been used in this capacity. The Marx generator is one obvious choice since it is relatively simple, efficient at voltage multiplication and can easily be designed at low impedances to match a given HPM load. However, Marx generators can be complex and conventionally have a large volume or weight to satisfy insulation and ancillary equipment requirements [3].

Some modern HPM applications benefit from compact and deployable pulsed power sources. Size, weight, and power consumption can become parasitic costs of a large energy store or power output. The minimization of these costs, along with ease of operation and maintenance, were driving factors in the design of this new class of Marx generator. This paper describes the design and performance of a 1.8-kJ, 600-kV Marx Generator system for HPM applications.

## II. DESIGN

The system overview for the APELC MG30-3C-100NF Marx Generator is shown in Figure 1. The Marx was designed to be compact, operate for an extended time on internal battery power, and meet the size, weight, and power listed in Table 1.

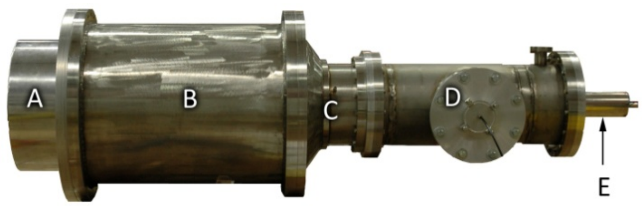


**Figure 1.** Main components of the APELC Marx Generator system: (A) power/control module, (B) Marx generator circuit, (C) diagnostic/transition flange, (D) load module, and (E) CVR.

**Table 1.** General Specifications of the Marx Generator System

| Symbol | Parameter | Value | units |
|---|---|---|---|
| L | Length | 1.25 | m |
| D | Diameter | 45 | cm |
| Wt | Total Weight | 170 | kg |
| $V_E$ | erected voltage | 600 | kV |
| $E_{pulse}$ | maximum energy / pulse | 1.8 | kJ |
| Charging elements type | | Inductive | |
| Output capabilities | | Vacuum interface and resistive dummy load | |
| Voltage output monitor | | capacitive voltage probe (BNC) | |
| Current output monitor | | B-dot coil current probe (BNC) | |

### A. *Marx Circuit*

The Marx circuit was designed for (1) compactness (2) low inductance, (3) pressurized dry air as the insulation medium, (4) simple maintenance and repair and (5) off-the-shelf capacitors to reduce production cost.

[⊥]email: cnunnally@apelc.com

Modular platters were designed to address these goals. The Marx circuit was made half as long as a typical APELC 30-stage Marx generator by including two Marx stages and two spark gaps per platter. Each stage consisted of three 100-nF mica capacitors from Custom Electronics, Inc. [4]. Each Marx stage is isolated by 25-uH inductors to allow for low loss charging in the future.

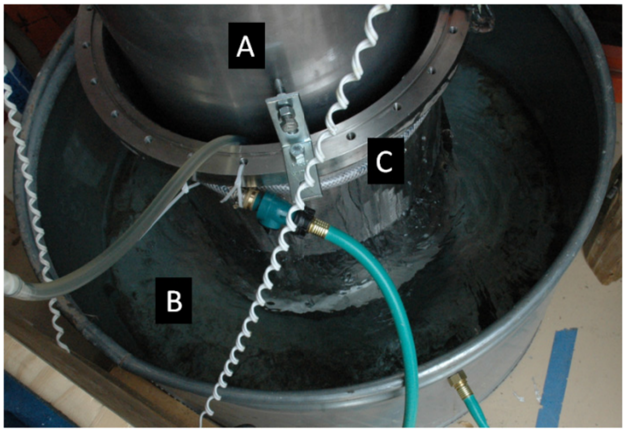


**Figure 2.** Epoxy curing setup showing (A) the epoxy mold, (B) room-temperature water heat sink, and (C) the Marx pressure vessel.

The Marx pressure vessel was fabricated out of 314 Stainless Steel and lined with a layered epoxy insulator designed for high-voltage insulation and proper stray capacitance. The epoxy liner was cured in a temperature-controlled chamber to address cracking issues cause by the curing process, as shown in Figure 2.

**Table 2.** Electrical Specifications of the Marx Generator

| Symbol | Parameter | Value | units |
|---|---|---|---|
| N | Number of stages | 30 | - |
| $V_E$ | erected voltage | 600 | kV |
| $V_{ch}$ | maximum charge voltage | 20 | kV |
| | charge voltage range | 5-20 | kV |
| $E_{pulse}$ | maximum energy per pulse | 1.8 | kJ |
| $P_{25}$ | Maximum power on a 25 ohm load | 5 | GW |
| $C_{stage}$ | Capacitance per stage | 300 | nF |
| | Erected capacitance | 11 | nF |
| $L_s$ | Series inductance | 6000 | nH |
| $Z_{source}$ | Source Impedance | 25 | Ohms |

The volume of the Marx circuit, epoxy liner, and pressure vessel was 0.36 $m^3$ for a volumetric energy density of 4.9 $kJ/m^3$. The electrical characteristics of the Marx circuit are listed in Table 2.

***B. Integrated Power Electronics***

The power electronics module shown in Figure 1(A) contains prime power, a high-voltage power supply from Acopian Technical Co., an APELC solid-state trigger unit, a digital pressure regulator, and all user controls and indicators [5]. From the front panel shown in Figure 3, the user selects the vessel pressure and Marx charge voltage. A fiber-optic remote control allows charge and trigger command from an extended distance. The power electronics module can be powered from an AC line source or on its internal battery pack for approximately 6 hours.


**Figure 3.** Control panel of the integrated power electronics module.

***C. Diagnostics***

Voltage and current diagnostics were integrated into the transition section, shown in Figure 4, between the Marx housing and a 12-in. Conflat vacuum flange on the output. The voltage diagnostic is a capacitive divider built into a 50-ohm transmission line. The current diagnostic is a pick-up coil housed in a shielded tube. The housing is grounded and enclosed except for a small B-field aperture which is arranged orthogonal to the center conductor.

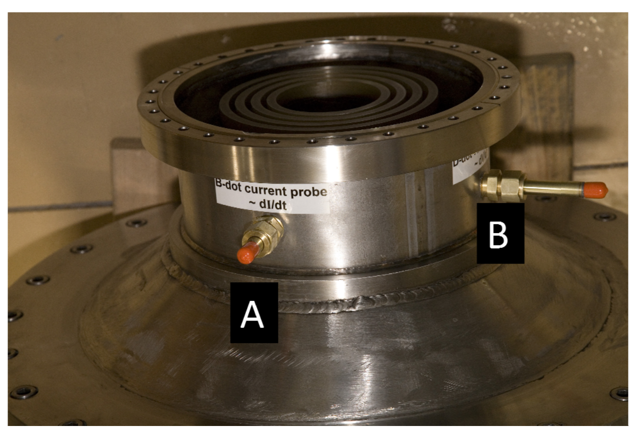


**Figure 4.** (A) B-dot current probe and (B) capacitive divider voltage probe integrated into the output section.

The shielded B-dot probe was designed to be immune to load-related noise common in HPM applications. Each diagnostic was packaged into a brass tube with a BNC fitting. Each brass tube was installed into a Swagelok fitting prior to the epoxy pour. A pressurized load chamber was fabricated to evaluate the pulse characteristics to resistive loads and calibrate the integrated diagnostics. As in Figure 1D-E, The load chamber was then terminated into a 50-Watt coaxial CVR made by T&M Research [6].

# III. PERFORMANCE

In order to evaluate the pulse characteristics of the finished system, the output pulse was measured for various resistor values and then discharged into a short circuit to measure the ringdown current pulse. In addition the two integrated diagnostics were evaluated against CVR waveform data.

## *A. Resistive-load Pulse Characterization*

Four resistors with values near the Marx impedance were installed in the pressurized load chamber. The load was then terminated into the CVR. The Marx was charged to 10 kV and discharged into the load module. The load current pulse was then measured using an 8-GHz, Tektronix TDS6804B oscilloscope. The load voltage pulse was calculated from the measured load resistance value. Figure 5 shows the load voltage waveforms for 10, 15, 25, and 30-Ω resistor values. At a 10-kV charge voltage the Marx delivered an approximately 150 kV pulse to a matched 25-Ω load. For the 10-Ω load, the voltage waveform is underdamped and reaches a peak voltage of approximately 80 kV.

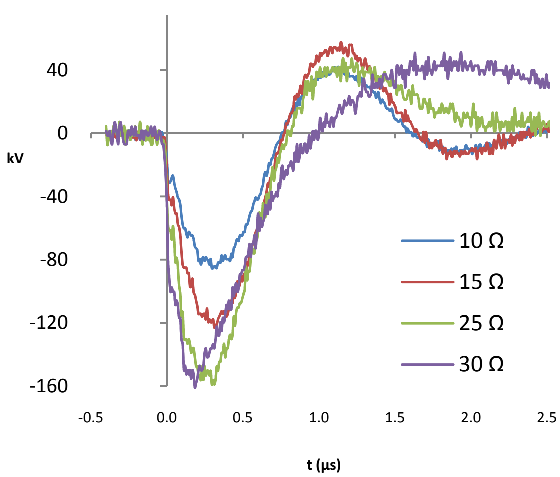


**Figure 5.** Load voltage waveforms for 10, 15, 25, and 30-Ω load resistors values.

## *B. Ringdown*

A ringdown was performed to assess the global impedance of the pulse generator. A brass cylinder was installed into the resistor housing in the load chamber and terminated directly through the CVR. The Marx was then charged to 10-kV (half-max) and discharged directly into the CVR.

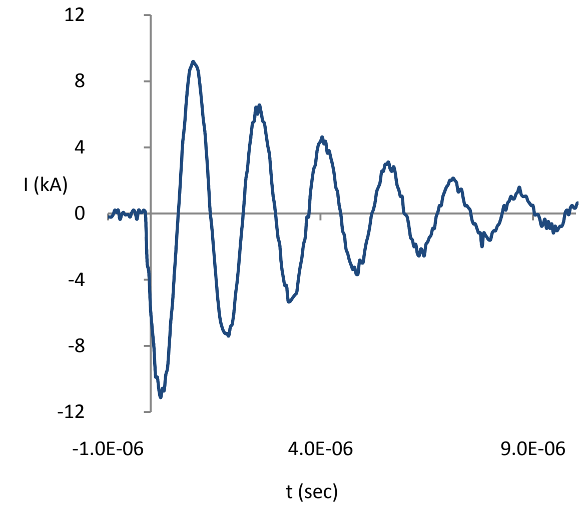


**Figure 6.** Ring down current pulse with Marx charged to 10 kV and terminated directly through the CVR module. The ringdown period was measured at 1.54 µs.

The ringdown period was measured to be 1.54 µs. The Marx inductance and impedance were calculated from the ringdown period as follows

$$L_{Marx} = \frac{1}{(2\pi f)^2 C_{erect}} = 6.01\ \mu H \qquad (1)$$

$$Z_{Marx} = \sqrt{\frac{L_{Marx}}{C_{erect}}} = 24.5\ \Omega \qquad (2)$$

## *C. Diagnostics*

The integrated diagnostics described here were intended to replace similar, but less effective diagnostics on the original Marx housing. The newer diagnostics were designed to have a larger signal:noise ratio and be more immune to load-associated noise when used in HPM applications.

In order to evaluate the response of the shielded B-dot current probe and the capacitive voltage divider independently of the Marx circuit, a pulse generator with a slightly faster risetime was discharged into the Marx pressure vessel, a 35-Ω load resistor and terminated through a 50-Watt CVR. The B-dot signal was attenuated 7 dB and measured by an 8-GHz oscilloscope. Figure 7 shows the numerically integrated B-dot waveform plotted against waveform generated by the T & M Research CVR.

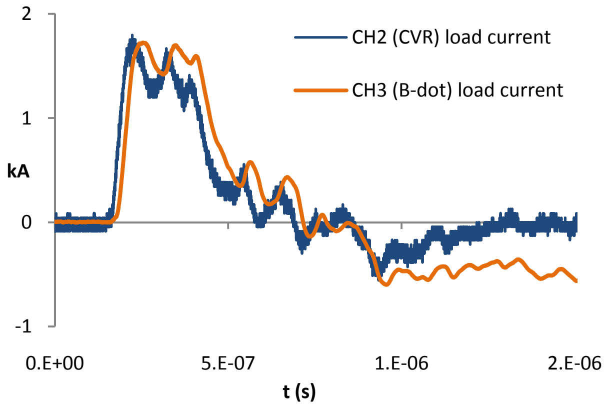


**Figure 7.** Shielded B-dot waveform plotted against CVR waveform for a 35-Ω resistive load.

In a similar manner, the capacitive voltage divider probe signal was attenuated 30 dB and terminated through the oscilloscope. The load voltage waveform acquired by numerically integrating the capacitive divider waveform is shown in Figure 8.

Both of these diagnostics displayed a good signal:noise ratio and both acceptably reproduced the waveform generated by the CVR, which in this analysis was considered standard.

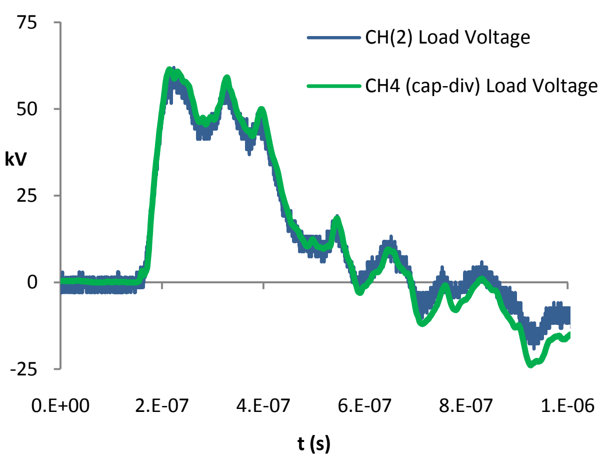


**Figure 8.** Capacitive Divider waveform plotted against CVR waveform for a 50-Ω resistive load.

# IV. CONCLUSIONS

This paper described the design and performance of a 1.8-kJ, 600-kV Marx generator system used for HPM applications. The risetime of the voltage pulse was typically measured to be < 100-ns into resistive loads between 10 and 30 Ω. The integrated power electronics and controls proved to be reliable while remaining compact. The system can run on internal battery power for up to 6 hours.

Improved integrated diagnostics provided a higher output signal and suffer less noise than previous versions. The inductance of the Marx generator as measured by the ringdown experiment proved to be several times larger than intended. This increase in inductance is partially due to the ESL of off-the-shelf capacitors with the required energy density, but also due to the platter to platter current path that results from the compact stage arrangement. A lower inductance arrangement is planned for the next generation Marx system.

# V. REFERENCES

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[6] T & M Research Products, 139 Rhode Island NE., Albuquerque, NM 87108.