Marx Generators for High-Power RF and Microwave Applications

Thomas Holt, Jon Mayes, Clay Nunnally, Matt Lara, Mark Mayes, Chris Hatfield, and Jeremy Byman
Applied Physical Electronics, L. C.
Austin, TX 78734
thomas.holt@ieee.org

***Abstract* — Recent technological advancements in the field of directed energy have led to increased demand for sources capable of driving high-power RF and high-power microwave (HPM) radiators. APELC's line of Marx generators are uniquely qualified for use in various directed energy applications. Extensive testing performed on a 33-J Marx generator, which has been used as a source to drive various RF loads, will be summarized. Testing included characterizing the thermal behavior of the Marx generator during operation at various pulse repetition frequencies as well as monitoring output pulse characteristics and reproducibility. Pulse characteristics for nine other Marx generators varying from 10 mJ to 1.8 kJ in output energy will also be provided. In addition, measured RF and HPM data from various radiators sourced by APELC's Marx generators will be presented.**

Keywords- Marx generator, HPM, directed energy, low-jitter, wideband

I. Introduction

Applied Physical Electronics, L. C. (APELC) has developed an assortment of wave-erection style Marx generators since the company's founding in 1998 [1]. The APELC family of Marx generators varies in size from an 8-in wide by 2-in long PCB to an 18-in diameter and 72-in tall cylindrical vessel, and covers an energy range from 2 mJ to 1.8 kJ. A selection of Marx generators offered by APELC will be summarized and data collected from high power RF and high power microwave (HPM) applications will be presented. The presentation of information that follows will be categorized according to the Marx generator and will be divided into a Marx generator performance section followed by an applications section. This paper constitutes a continuation and update to the previous document with a similar title [2].

II. A Sample of APELCs Marx Generators

The specifications for APELC's line of Marx generators are summarized in Table 1. They vary in size from an 8-in wide by 2-in long PCB to an 18-in diameter and 72-in tall cylindrical vessel and cover an energy range from 2 mJ to 1.8 kJ.

Each Marx generator listed in Table 1 is identified by a model number that has the following form; MGXX-YYC-ZZZZWF. XX represents the number of Marx generator stages, YY enumerates the number of capacitors per stage, ZZZZ defines the magnitude of a single stage capacitor, and W identifies the scale for the capacitance unit (i.e. NF for nanofarad, and PF for picofarad). The MG15-3C-940PF, for example, is a fifteen-stage Marx generator with three 940-pF capacitors per stage.

A. *Circuit Board Marx Generators*

APELC has developed circuit-board-level Marx generators using solid-state TRAPATT diode switches, gas-discharge switch circuit board Marx generators, and conformally-mapped co-planar waveguide generators. The generators have the capability to be powered by conventional battery packs at repetition rates over 100 Hz and can deliver up to 1 MW peak power to a matched load for each pulse. Figure 1 shows an output voltage waveform from a gas-discharge switch Marx generator (MG10-1C-1NF).

B. *MG15-3C-940PF*

The MG15-3C-940PF (or MG15) is APELC's staple Marx generator and is used extensively in many applications due to its 50-Ohm impedance. The MG15 can be operated at a 200-Hz pulse repetition frequency (PRF) at 40-kV charge voltage. The extensive use of the MG15 in a variety of applications has generated voluminous amounts of performance data, which are summarized in the sections that follow.

1) *Burst-Mode Performance*

The burgeoning directed energy (DE) field has created demand for compact, robust, and energy-dense pulsed power generators. APELC adapted its MG15 for burst-mode operation in 2006 to meet the aforementioned demands of the DE field. The MG15 is a dry-air insulated and cooled pulsed power system that is capable of limited burst-mode operation at full charge voltage at a maximum PRF of 200 Hz. An overlay of eighteen sequentially-fired output waveforms from an MG15 operating at 200-Hz PRF and a maximum charge voltage of 40 kV are provided in Figure 2 (a). Verification of the claimed PRF and charge voltage level is provided by the charge voltage waveforms in Figure 2 (b). The MG15 was charged with a Lambda-TDK 802-L HVPS (a constant current supply), which limits the MG15 to a maximum achievable PRF of 210 Hz (including 1 ms of clear time between Marx events). Higher

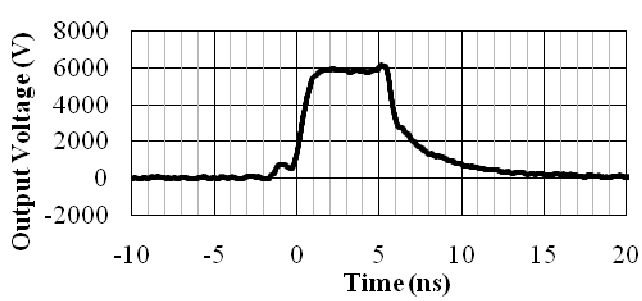

Figure 1 – Output voltage waveform from a 10-stage circuit board Marx generator driving a 50-Ohm load.

Table 1 – Summary of Marx generators

Model Number	Maximum Charge Voltage	Maximum Energy per Pulse	Peak Erected Voltage	Estimated Marx Impedance	Rise Time	Length	Housing Diameter/ (Width)	Maximum PRF verified/(predicted*)
	[kV]	*[J]*	*[kV]*	*[Ω]*	*[ns]*	*[in]*	*[in]*	*[Hz]*
MG10-1C-1NF	1	0.005	10	< 50	0.8**	8	(2)	50/(1000)
MG15-3C-940PF	40	33	600	52	0.5 – 5	31 – 36	5	200/(300)
MG40-3C-2700PF	40	266	1,600	70	1 – 7	72	8	4/(80)
MG20-1C-100NF	20	400	400	20	~100	41	10	10/(50)

*Predicted values assume an optimized Lambda-TDK 303-L power supply with no size or weight constraints.
** Rise time calculated using 20% - 80% standard. All other rise times quoted using 10% - 90% standard.
Additional models available but not discussed in this manuscript: MG17-1C-500PF, MG17-1C-940PF, MG10-1C-940PF, MG10-1C-2700PF, MG16-3C-2700PF, MG30-3C-100NF, MG20-22C-2000PF, MG20x8-3C-2200PF-PFN.

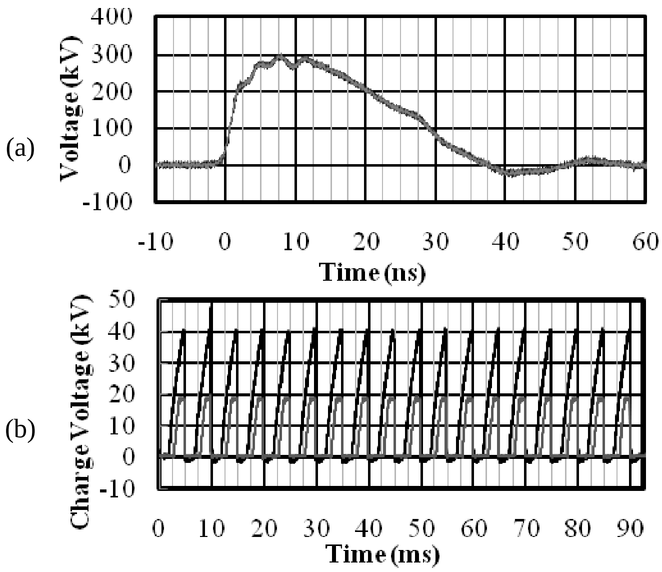

Figure 2 – (a) Superposition of 18 output waveforms measured during burst-mode operation at 200-Hz PRF at maximum charge voltage. (b) Corresponding Marx generator (black) and Trigger generator (gray) charge voltage waveforms.

PRFs are achievable by using a higher power HVPS but have not yet been tested.

2) Lifetime Study

Accurate prediction of the lifetime of a Marx generator is dependent upon a confluence of operational parameters. It is highly probable that an MG15 operated in single-shot mode with minutes of downtime between shots could outlive an experimenter with minimal maintenance. It is equally probable that an MG15 operated at maximum charge voltage and PRF would fail thermally within 20 seconds of continuous operation.

APELC developed a LabView-controlled, automated Lifetime testbed to monitor the electrical input and output signals as well as the internal thermal condition of various MG15 components during operation at various charge voltage levels and PRFs. Thermal conditions of internal components were monitored by an Omega FOB104 temperature sensor capable of measuring temperature from four independent fiber optic thermometers with a switching rate of 250 ms between channels. Data recorded from electrical diagnostics are withheld due to their similarity to the results presented in Figure 2.

Experimentation showed that the highest thermal stress occurred at the spark gap electrodes and that a thermal gradient was present in the direction of the MG15 erection. The thermal gradient corresponds directly with the increasing electron energies that bridge each subsequent spark gap during the MG15 erection (due to wave erection). Example thermal data acquired at 30-kV charge voltage during a 15-sec burst at 200 Hz PRF is provided in Figure 3. It was found, through testing to failure, that a temperature of approximately 210° F on the fourteenth stage temperature diagnostic marked the onset of thermal failure of the MG15. This closely corresponds to the upper service temperature of the insulating material found in direct proximity to the electrode pairs. The thermal data collected over the course of the lifetime testing yielded the list of acceptable burst lengths provided in Table 2. It should be noted that the acceptable burst length is not the maximum achievable burst length, rather the maximum burst length safely tested and, consequently, recommended by APELC for reliable operation of the MG15. Thermal relaxation profiles were also monitored and typically showed that under constant flow of approximately 3 scfm, a 1 minute purge following a burst would cool the MG15 to a temperature that would accommodate any subsequent burst as defined in Table 2.

The shot log kept during the lifetime study indicated that a total of 239,120 shots were fired at different charge voltage levels on the same spark gap electrodes for a total charge transfer, Q_T, of 16.2 Coulombs. The minimum expected electrode lifetime measured in number of shots, N_E, at various charge voltages, V_C, can be computed using Equation (1), and totals 143,324 shots at full voltage. The Marx that was used for the lifetime study remains in service to this day.

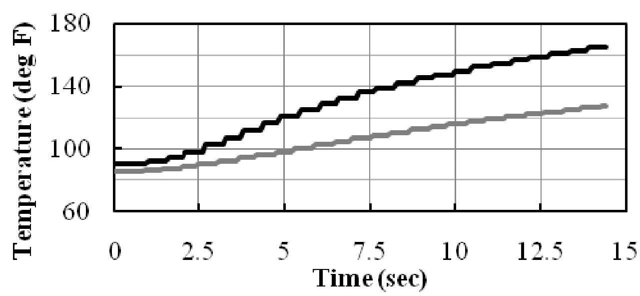

Figure 3 – Temperature monitoring for the buswork near the high-side spark gap electrode for the eighth (gray) and fourteenth (black) stages. Data were accumulated during burst-mode operation as summarized in Table 2.

Table 2 – Summary of Acceptable Burst Lengths for different operating conditions

Charge Voltage	PRF	Acceptable Burst Length
[kV]	*[Hz]*	*[sec]*
20	100	150
20	200	50
30	100	40
30	200	15
35	100	10

$$N_E = {Q_T}/{(V_C \times C_{STAGE})} \quad (1)$$

3) TTL to Marx Output Jitter

Applications requiring low jitter between a TTL-level trigger command and a subsequent high voltage output pulse can be accommodated by APELCs line of Marx generators. An overlay of 19 TTL and Marx output waveform pairs is provided in Figure 4. The waveform pairs are provided in arbitrary units as the relative timing between the 50% points is the only parameter of interest. Analysis shows that the Marx event follows an average of 45.36 ns after the trigger command with a jitter of 1.84 ns. Additional jitter measurements were presented in [3].

4) Peaking Circuit

Many applications, such as direct radiation of Marx generator output, require the use of a peaking circuit to achieve output pulse rise times that can be efficiently radiated by antennas that are not prohibitively large. APELC developed a modular peaking circuit that replaces a traditional MG15 output section and is capable of achieving sub-nanosecond rise times when driving a cable load of matched impedance, as summarized in Table 3. This demonstrates a significant improvement over the standard rise time of 4.69 ± 0.15 ns (10-90) and 3.41 ± 0.26 ns (20-80) and an even greater improvement over the results presented in [4]. High pressure (> 1000 psi) breathable dry air confined to the modular output section is used as the insulating dielectric. APELC also is capable of integrating crowbar switches into modular output sections to control output pulse fall time.

C. MG20-1C-100NF

The MG20-1C-100NF (MG20) is a 20-Ω, 400-J Marx generator suitable for driving HPM loads such as a vircator. Output voltage waveforms acquired with a 20-Ohm load operated in burst mode are provided in Figure 5.

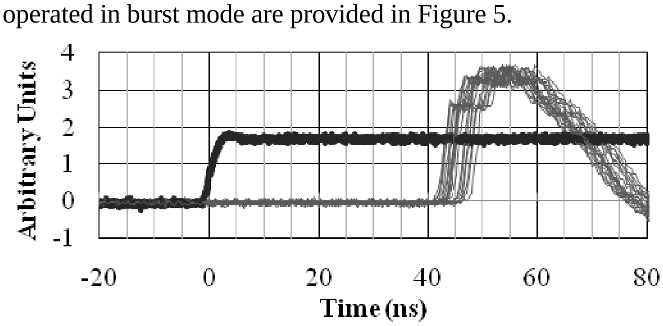

Figure 4 – Jitter measurement data for an MG15 operating at 75% of full charge voltage. The black traces are a TTL reference pulse provided by a delay generator used to initiate the Marx event and the gray traces are the MG15 output waveforms.

Table 3 – Various rise times corresponding to different MG15 charge voltage levels

Charge Voltage	Rise Time (10-90)	Rise Time (20-80)
[kV]	*[ns]*	*[ns]*
20	0.48	0.22
30	2.48	0.85
35	0.67	0.59

III. Applications

Throughout the past decade, APELC has applied its Marx technology in a variety of different areas. The following sections summarize recent applications, within the past three years, of APELCs line of Marx generators in the DE field.

A. MG15-3C-940PF

The MG15 has seen the most use by APELC and other customers for a variety of applications including directly sourcing a variety of impulse radiating antennas and pulse charging various resonating loads. The following are a small selection of APELCs applications involving the use of an MG15-like Marx generator.

1) APELCs Suite of Wideband Dipole Radiators

APELCs suite of proprietary wideband dipole radiators presently covers the frequency range from 100 MHz to 400 MHz which are driven by the MG15. Peak electric field amplitudes exceeding 200 kV/m when normalized to a distance of 1 m have been recorded. Figure 6 is an electric field measurement made by an undisclosed third party and demonstrates the burst mode capability of the 400-MHz wideband dipole system.

2) Additional Applications of the MG15

A modified MG15 was used to directly source a semi-transparent TEM horn feeding a parabolic reflector. A peak electric field of greater than 200 kV/m normalized to 1 m was achieved. Additional details are provided in [5].

APELC developed an EMP test-bed that accommodates a device under test as large as 40” x 24” x 16” (length x width x height). The test-bed can be driven by two separate front-end modules which meet the RS-105 and RS-05 testing standards as defined by MIL-STD 461 C/E/F. A modified MG15 is the basis technology used to drive the EMP test-bed. Additional information on APELCs EMP Test-bed can be found in [6].

B. 12-ft Radiating Dish sourced by the MG40-3C-2700PF

An impulse radiating antenna similar to the 6-ft radiating dish was developed using the MG40-3C-2700PF (MG40) as the source. The MG40 was modified to accommodate a peaking circuit [4], then adapted to a custom RF transition that fed a 12-ft diameter, fiberglass parabolic reflector. The RF transition consisted of a coaxial-to-parallel plate transition that converted the 70-Ohm coaxial Marx generator output to a 110-Ohm parallel plate TEM-horn feed. The parallel plate feed section had a two-way transit time of 10 ns prior to flaring off to feed the pseudo-transparent TEM horn. The TEM horn was constructed with telescoping arms and the Marx generator rested on sliding rails to allow for real time positioning of the phase center given the operating conditions of the Marx generator.

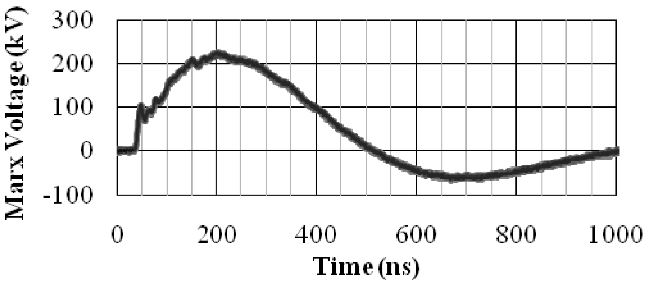

Figure 5 – Superposition of 10 output waveforms measured during burst-mode operation at 10-Hz PRF at maximum charge voltage.

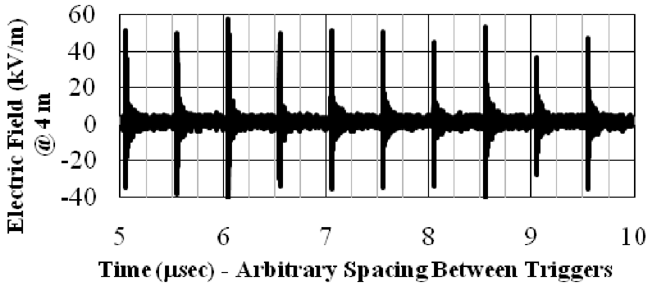

Figure 6 – A small sample of waveforms captured from APELCs 400-MHz dipole radiator by a third party. The waveform above was constructed by stacking independent trigger events comprised of 500-ns windows of data over the course of a burst of 200 shots fired at a repetition rate of 150 Hz. The diagnostic was a Nanofast 709-1 EFS and was at a distance of 4 meters from the dipole radiator.

A measured impulse recorded using an AH-Systems model SAS-570 double ridged horn as a receiving antenna is shown in Figure 7 (a) and the corresponding spectral density is shown in Figure 7 (b). The center frequency of the main radiated impulse is near 400 MHz, however, the low frequency (200 MHz) and comparatively lower amplitude (~ 70 kV/m) ringing dominates the spectral density. System size prohibited a complete mapping of the antenna pattern; however, an H-plane mapping was performed. As expected, the main lobe is along the bore sight of the system (in the direction normal to the parabolic reflector) and has a 3-dB beamwidth of approximately 18 degrees. The far field of the antenna is estimated to begin between 11.1 m and 38.4 m from the aperture of the dish depending on the far-field criterion applied and the center frequency chosen.

C. Microwave System sourced by the MG20-1C-100NF

A first-generation planar vircator was driven by the MG20 and marked APELCs first foray into the realm of HPM source development. The observed center frequency from the data presented in Figure 8 swept from near 1.5 GHz to 2.8 GHz. A second-generation cathode is under development and additional steps are being taken to improve performance.

IV. Conclusions

APELC is working diligently to meet the demands of compactness, robustness, and repetition rate performance placed on systems required by the DE field. The sources and applications listed herein and others too numerous to include demonstrate APELCs growing breadth of experience that can be applied to realize deployable DE systems.

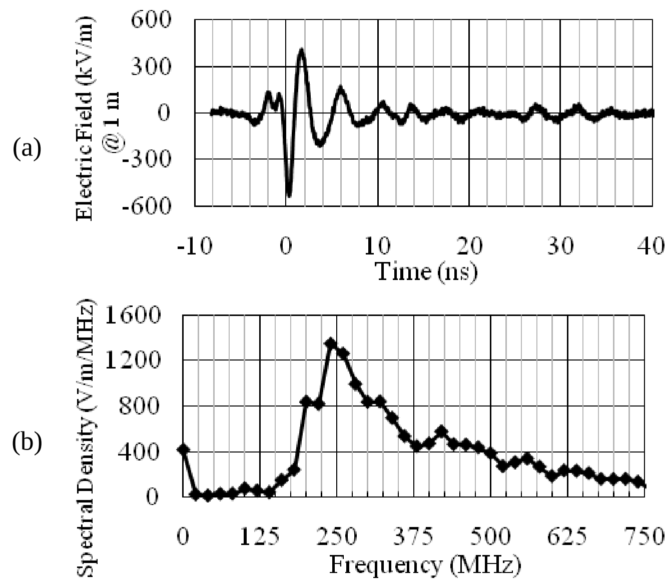

Figure 7 – (a) A measured radiated impulse from the 12-ft Radiating Dish normalized to a distance of 1 m and (b) the corresponding spectral density. The accuracy of the amplitude in (a) is frequency dependent and is expected to be within 20% of the true amplitude of the radiated signal.

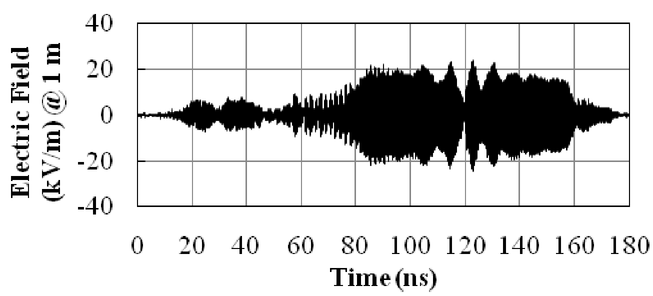

Figure 8 – Microwave output from APELCs first generation microwave load sourced by the MG20-1C-100NF.

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