DESIGN AND PERFORMANCE OF A 4 MV, 14 KJ MARX GENERATOR

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Abstract

Applied Physical Electronics, L.C. (APELC) has designed, built, and characterized a large Marx generator capable of a maximum erected voltage of 4 MV and a maximum pulse energy of 14.5 kJ. The generator is charged using a dual polarity charging topology, which helps reduce the source impedance to approximately 70 Ohms. When driving a matched resistive load, a peak power of 230 GW is delivered, with an approximate rise time of 100 ns and a pulse width of approximately 300 ns. The generator is uniquely designed to be generally insulated with transformer oil, but switched in a dry air medium. The 42 spark gap switches are uniquely grouped in sets of six, bringing in the advantages of UV coupling, and gap pre-ionization, to better switching performance.

I. INTRODUCTION

Large-scale Marx generators have utility in a number of applications requiring very specific pulse characteristics, including high-dose flash x-ray and Electro-Magnetic Pulse simulators. Typically, these generators produce the desired peak voltage and the necessary energy required by the load. With very good design technique, the Marx generator can also meet the desired temporal pulse characteristics. APELC has recently built such a Marx generator.

The primary focus of this effort was to design and build a generator with a wide voltage operation that is stable in its performance, while also being very robust and easily maintained. This generator has a target erected voltage of 4 MV, a voltage rise time into a matched resistive load of less than 200 ns, and a pulse width (FWHM) of 172 ns.

II. THE MARX GENERATOR DESIGN

The primary design goals included: a maximum erected voltage of 4 MV, a minimized series inductance to achieve a generator impedance of 70 Ω, a large voltage operating range, a low shot-to-shot variance; and minimal failures of long lead-time components.

The overall design centers on commercial off-the-shelf capacitors manufactured by CSI Technologies. The remainder of the components were manufactured by APELC. The Marx generator components are insulated with transformer oil, which enables a compact design. However, the desire for a wide voltage operating range necessitates the use of pressurized, dry breathable air as the switching medium. Furthermore, a bi-polar charge topology was chosen to reduce the number of spark gaps.

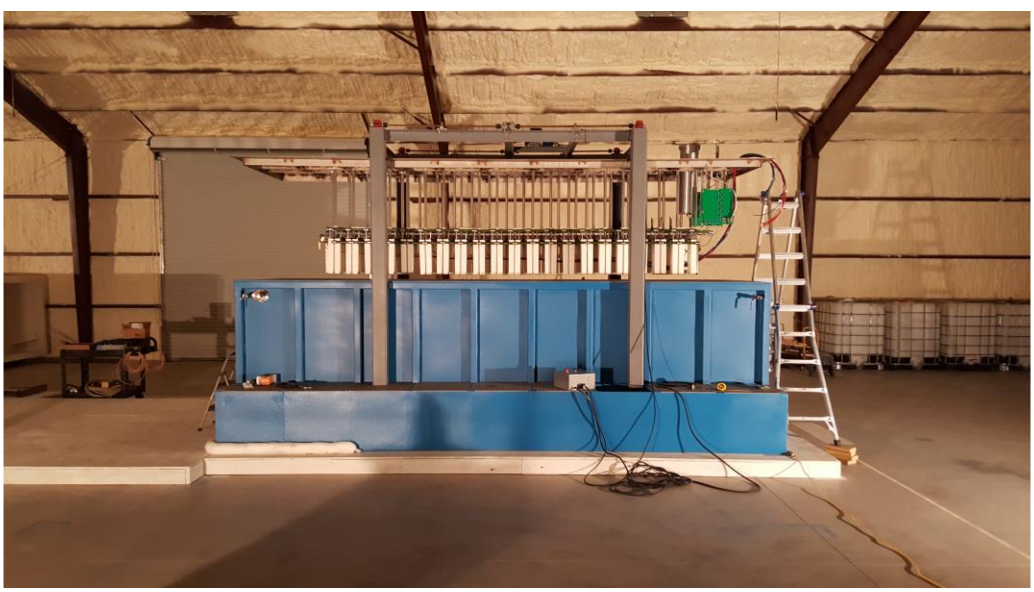

Figure 1. The APELC 4 MV Marx generator.

The spark gap switches were packaged in large, plastic blocks, designed for pressures of up to 200 psi. Because the overall design uses a large number of spark gaps, spark gaps were bundled in sets of six, so that each "switch block" contained six spark gap switches, with each designed to hold off the differential voltage.

The first switch block is the triggered-block. All six spark gaps are fitted with field distortion gaps, and driven by a common, compact Marx generator. The remaining five switch blocks contain self-break spark gap switches.

The triggering process begins with an 18 kV pulse delivered by a thyratron-based unit. This pulse drives a trigatron located in the compact Marx generator, which in turn drives the field distortion gaps located in the triggered switch block of the primary Marx generator. The primary Marx generator relies on a cascading, wave erection process.

The compact Marx generator, which can also be described as the "stage-2 trigger" generator, is described in Table 1. This generator is a simple 10-stage design, capable of delivering an erected voltage of up to 300 kV. The generator is compact, with a length of 36 inches and a diameter of 9.5 inches. The generator is insulated with solid dielectrics and pressurized, dry, breathable air. Because it is hermitically-sealed, most of the generator is located inside the transformer oil of the primary generator, thus minimizing the connection inductance.

Table 1. Trigger generator specifications

Parameter	Value	Units
Number of stages	10	-
Peak erected voltage (matched load)	300	kV
Maximum charge voltage	30	kV
Maximum energy per pulse	36	J
Capacitance per stage	8.1	nF
Erected capacitance	810	pF
Series inductance	500	nH
Source impedance	25	Ohms
Housing length	36	in
Housing diameter	9.5	in

The primary generator is described by Table 2. The design uses 83 capacitors, 42 spark gap switches, and is based on a dual polarity charge scheme. The basis capacitor is a 150 nF, 70 kV model manufactured by CSI Technologies. The 4MV design for the Marx generator was was vetted using standard design guidelines, and modeled using Maxwell 3D. Additional field grading was included at the output of the generator to prevent breakdown at the highest potential. The final package of the generator fits a volume described as 226 inches x 67 inches x 60 inches (L x W x H), and uses approximately 3,000 gallons of transformer oil.

Two water resistors are located at the output of the generator. Each resistor is connected to the housing via current viewing resistors (T&M model K-1-500). The parallel resistors reduce the load inductance, while also providing some insurance against the generator erecting into an open circuit, caused by a resistor failure. The resistors can also provide tunable pulse shaping in order to meet the requirements of the final deliverable.

Table 2. Primary generator specifications

Parameter	Value	Units
Number of stages	83	-
Peak erected voltage (matched load)	4	MV
Maximum charge voltage	50	kV
Maximum energy per pulse	14.45	kJ
Capacitance per stage	150	nF
Erected capacitance	1.81	nF
Series inductance	8	μH
Source impedance	73	Ohms
Housing length	226	in
Housing height	67	in
Housing width	60	in

III. GENERATOR PERFORMANCE

The stage-2 trigger generator was bench-tested first. As shown in Figure 2, a CVR was connected to the output of the generator so that the generator's inductance can be derived from a resonant ring down. Figure 3 shows the ring-down waveform from a shot with the generator operating at atmosphere. A frequency of approximately 6.67 MHz was measured. With an approximate output inductance of 200 nH, and an erected capacitance of 810 pF, the generator is calculated to have a series inductance of 500 nH, resulting in an impedance of 25 Ohm.

Figure 2. The stage-2 trigger generator being bench-tested for a ringdown test.

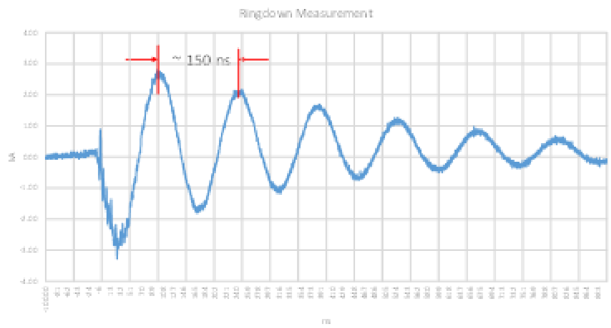

Figure 3. The ring down waveform for the stage-2 trigger Marx generator.

The testing of the main Marx generator began with a ring down measurement, to ultimately determine the generator's impedance. The load water resistors were by-passed with large grounding straps, so that the CVRs measure the short-circuit currents. Figure 4 provides a sample ring down waveform, noting the period measurement. With a frequency of 1.2 MHz, and an erected capacitance of 1.81 nF, the series inductance of the generator is calculated to be 9.7 µH, which resolves an impedance of 73 Ohm.

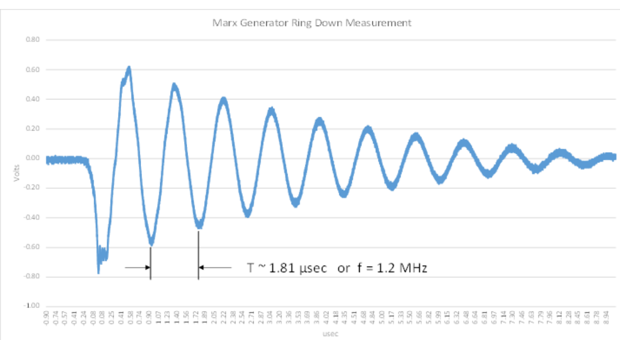

Figure 4. The ring down waveform for the primary Marx generator.

A Paschen curve is derived for the primary Marx generator. For this measurement, two constant voltage high voltage DC power supplies, of opposite charge polarity, are used to slowly charge the Marx generator. For each pressure setting, 20 samples were taken and averaged. Figure 5 provides several Paschen curves for the current spark gap settings, and related to several operating points. The top trace defines the actual Paschen curve, or the average voltage breakdown for each pressure setting. The additional curves are simple percentages, provided to help the customer know the operating points.

The two parallel load resistors were each made to a resistance of 140 Ω, yielding a 70 Ω total resistance. The generator was then tested throughout the charge voltage range to determine performance characteristics. Figure 6 provides several output waveforms, versus the charge voltage. The initial voltage rise is very fast, finding its intermediate peak (~ 78%) within 18 ns. This fast rise is inherently due to the stray capacitance of the Marx generator. Following the initial peak, the series inductance of the Marx generator comes into play, and the final peak is found at 146 ns, giving us 10 – 90% rise time of approximately 100 ns. The wave shape of the output pulse is consistent over the charge voltage range.

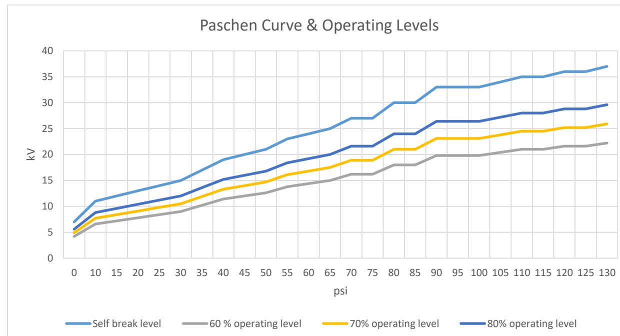

Figure 5. The Paschen curve measured for the primary Marx generator.

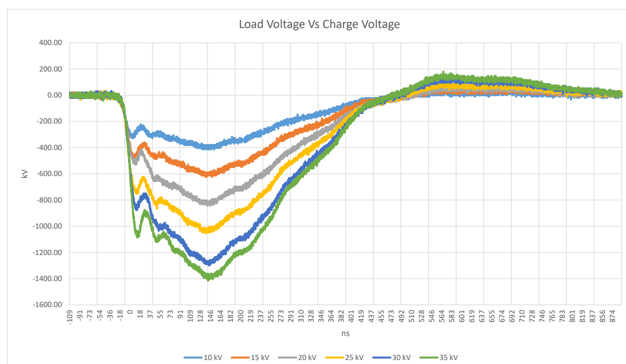

Figure 6. Output waveforms from the primary Marx generator driving a resistive 70 Ω load. The charge voltage excursion is from 10 kV to 35 kV.

The peak value of the waveforms shown in Figure 6 correspond well with theory, with 50% of the voltage seen across the resistive load. We do see some negative swing, likely due to the inductance in the load. The 10 – 35 kV represents an operating range of approximately 3.5X. It is noted that the gap spacing in the switch blocks can be changed to move the charge voltage operating range up or down, depending on the application's need.

To study the waveform jitter, shot sequences were taken, and various points within the waveform were analyzed. Figure 7 provides a sample sequence, with the generator being charged with ±30 kV. Focus was placed on the initial peak and the primary peak. From a 25-shot sequence, a standard deviation of 1.5% was determined at the initial peak, and a standard deviation of 0.74% at the primary peak- demonstrating a very stable output waveform.

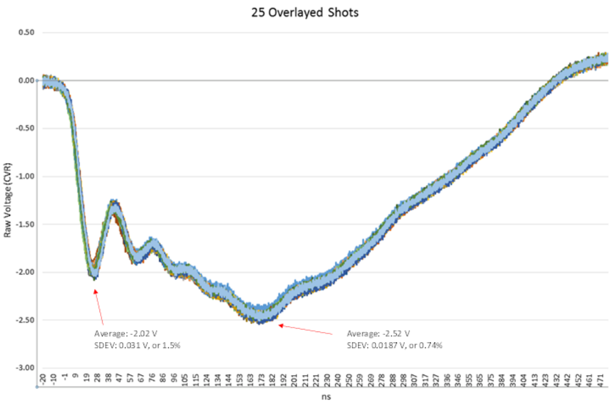

Figure 7. An overlay of a 25 shot sequence from the primary Marx generator driving a resistive 70 Ω load.

IV. CONCLUSION

APELC has built a large-scale Marx generator that is part of a larger pulsed power system. This generator is capable of erecting 4 MV, and delivering up to 2 MV into a matched 70 Ω load. The output waveform is very stable over a wide voltage range (3.5X). The operating range can be moved, so as to capture the maximum ± 50 kV charge to achieve the maximum erected voltage. This paper has described the basic design and described the general benefits of the designs. The basic characteristics of the system were studied in presented, including general operating characteristics and waveform stability. Future work will describe the full pulsed power system, which includes the pulse conditioning and controls.

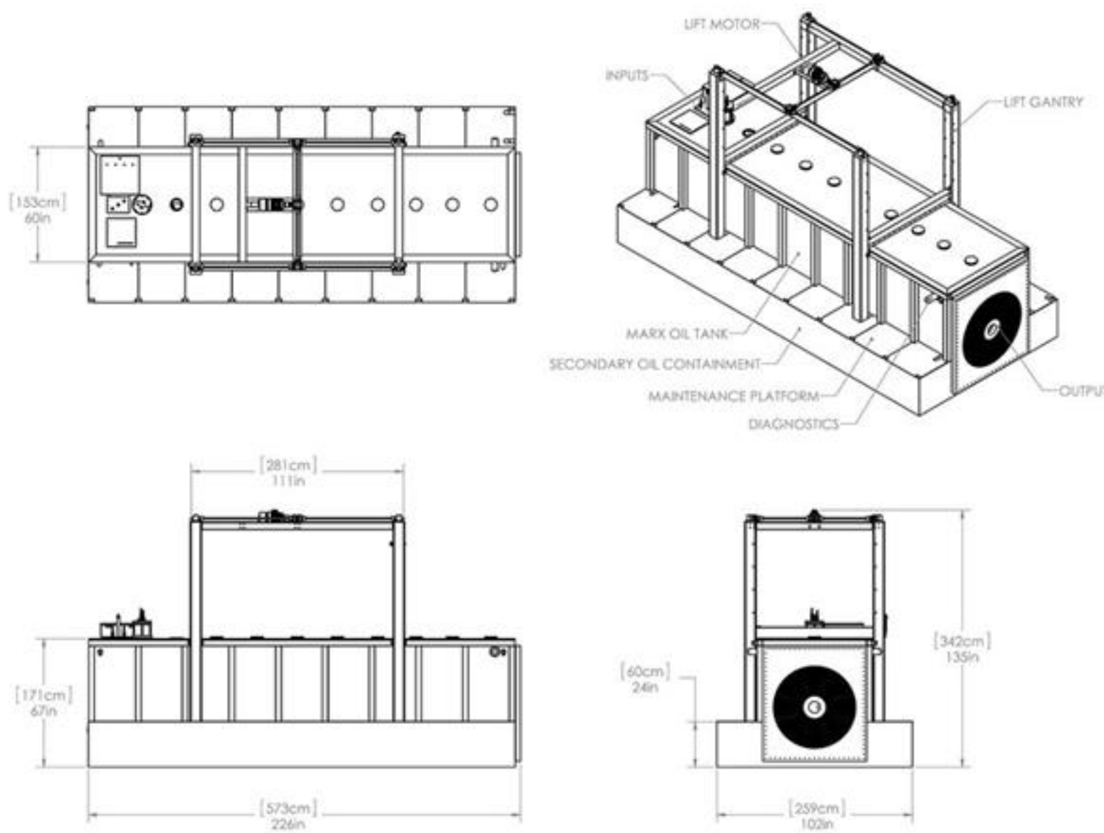

Figure 8. Dimensioned drawings of the Marx generator.