COMPACT MARX GENERATORS MODIFIED FOR FAST RISETIME

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Abstract

Traditionally, the 1.6-MV Marx generator offered by APELC operates at a charge voltage of 40 kV, an erected voltage of 1.6 MV, a stored energy of 260 J, and an output pulse rise time between 6-8 ns. APELC has developed a pulse conditioning system (PCS) that can be retrofitted into the existing MV Marx generator housing to improve output pulse rise time at a minimal cost of stored energy. The performance characteristics of the newly developed PCS driven by a slightly modified version of APELC's MV Marx generator will be provided. APELC has also retrofitted its staple 15-stage, 33-J, Marx generator with a scaled version of the same PCS. Preliminary results of the scaled version of the PCS are presented as well.

I. BACKGROUND

The Marx generator has been used for a wide variety of applications requiring voltage multiplication in the pulsed power field. Applications range from using the Marx generator as the first stage of pulse compression in high energy accelerators such as the ZR [1] to solid-state drivers for HPM diodes [2]. Consequently, the size, weight, and geometry of a Marx generator can vary wildly depending on the application from room-sized devices down to solid-state devices. All applications, however, use the Marx generator to convert energy stored in capacitors at a low potential over a long time scale to a higher potential, short time scale discharge by dynamically switching the capacitors to a series configuration.

Due to the proliferation of Marx generator technology in the pulsed power field, a solid understanding of the operation of the different types of generators can be garnered from various textbooks and journal articles. The operation of the Marx generators described herein is well described in [3] and [4].

II. APELC MARX GENERATORS AND POWER CONDITIONING

The application of Marx generator technology is obviously dependent on the objective of the system incorporating the technology. Table 1 is an abridged listing of the Marx generators offered by APELC and potential applications for each type of Marx generator. APELC has been developing compact to mid-sized Marx generators (using the classification presented in [3]) for more than a decade and proposed using their proprietary Marx generator technology to directly source RF and HPM loads as early as 2001.

Table 1. Abridged listing of Marx generators offered by APELC and potential applications

Marx Generator	V_{LOAD} (Matched)	Applications
MG17-1C-500PF	255 kV	RF, materials studies, triggering
MG17-1C-940PF	255 kV	RF, triggering
MG15-3C-940PF [5]	300 kV	Pulse coded RF
MG16-3C-2700PF [6]	320 kV	RF
MG40-3C-2700PF	800 kV	RF, Flash X-ray
MG30-3C-100NF [7]	300 kV	HPM

Sourcing RF antennas directly with Marx generators requires output pulse risetimes below 1 ns in most cases. This is intuitive as the spectral content of the radiated signal must be applied to the transmitting antenna by some method. Sourcing the antenna directly with a Marx generator implies that the spectral content of the radiated signal must be present in the Marx output pulse. A rough approximation of the center frequency, f_c, generated by a particular rise time, t_r, is given as,

$$f_c = 0.35 * \frac{1}{t_r}. \quad (1)$$

Given the formula in Eq. (1), a 1-ns rise time corresponds roughly to a center frequency of 340 MHz. The more appropriate method for determining the center frequency would be to take the Fourier transform of the measured signal, however, Eq. (1) provides a good initial system design guideline.

Some HPM systems also place constraints on the output pulse fall time which necessitates the use of additional output pulse conditioning. Additionally, RF systems would radiate with greater efficiency if the systems were equipped with pulse conditioning that

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converts the double-exponential Marx output pulse to an oscillating output pulse with a frequency corresponding to the desired frequency of radiated energy. APELC is developing solutions to generate rectangular pulses with defined rise and fall times as well as converting the standard Marx output to an oscillatory output through various pulse conditioning systems (PCSs). The focus of this paper, however, is solely on presenting results achieved thus far on peaking circuit development and the resulting rise time reduction realized with the incorporation of the developed technology.

III. MG40-3C-2700PF

The APELC MG40-3C-2700PF (referred to as the LM3C) is a 40-stage Marx generator capable of delivering a peak output voltage of 800 kV into a matched load. This represents an instantaneous peak power of 9.1 GW delivered to the load. The impedance of the LM3C was measured to be nearly 70 Ohms as reported previously. The Marx uses dry air as the insulating gas and can be pressurized up to 150 psi. Additional LM3C specifications are listed in Table 2.

Table 2. Specifications of the MG40-3C-2700PF

Parameter	Value	Units
Length	1.87	m
Diameter	24.1	cm
Weight	115	kg
Number of Stages	40	--
Erected Voltage (open circuit)	1.6	MV
Charge Voltage	40	kV
Capacitance per Stage	8.1	nF
Erected Capacitance	203	pF
Source Impedance	70	Ohms

A. Baseline Performance

The internal configuration of the Marx generator ultimately determines the output waveform rise time and pulse width (to the degree to which stray inductances can be adjusted). A Marx tuned for high operating pressure can produce an output waveform with a faster rise time than one tuned for a lower operating pressure. The LM3C used for testing was operated at ~ 90 psi at a charge voltage of 30 kV and is representative of an LM3C operated under normal conditions (i.e. not optimized for fast rise time). The measured output pulse, shown in blue in Figure 1, had a FWHM of 39.6 ns with a 10-90 rise time of 7.6 ns and a 20-80 rise time of 4.4 ns. The LM3C was adapted to a cable load with an impedance of 41 Ohms and it provided 50-ns one-way transit time isolation and was terminated into a 50-Ohm load. The rise times quoted above are typical of an LM3C when operated in a standard configuration.

B. Pulse Conditioning

A PCS was added in series with the output of the LM3C. Due to the physical constraints of the housing, four Marx stages had to be removed to accommodate the PCS. APELC conducted experiments to determine the optimal PCS configuration by adjusting traditional parameters such as gap spacing, insulating gas type, and insulating gas pressure. The best results achieved thus far, shown in red in Figure 1, are a FWHM of 37.8 ns with a 10-90 rise time of 7.6 ns and a 20-80 rise time of 1.9 ns. While the 10-90 rise time for the system equipped with a peaking circuit did not improve, the 20-80 rise time showed significant improvement and an FFT analysis verified the presence of a larger amplitude of spectral content near 150-200 MHz.

The PCS was designed to act as a peaking circuit where a finite stray capacitance to ground was designed into the PCS just prior to the output switch. The capacitance of the peaking circuit was a small fraction of the erected capacitance of the Marx generator which should result in ringing voltage gain between the Marx and the peaking capacitance. This behavior was not seen, however, as no overshoot was observed on the output waveform. The prepulse observed was caused by capacitive coupling through the output switch. The capacitance of the output switch was kept below 10% of the peaking capacitance and was verified through 3D electrostatic field simulations performed in Maxwell 3D as well as through measurement with an LCR meter.

I. MG15-3C-940PF

The APELC MG15-3C-940PF (referred to as the SM3C) is a 15-stage Marx generator capable of delivering a peak output voltage of 300 kV into a matched load. This represents an instantaneous peak power of 1.7 GW delivered to the load. The impedance of the SM3C was measured to be nearly 52 Ohms as reported in [7]. The Marx uses dry air as the insulating gas and can be pressurized up to 150 psi. Additional SM3C specifications are listed in Table 3.

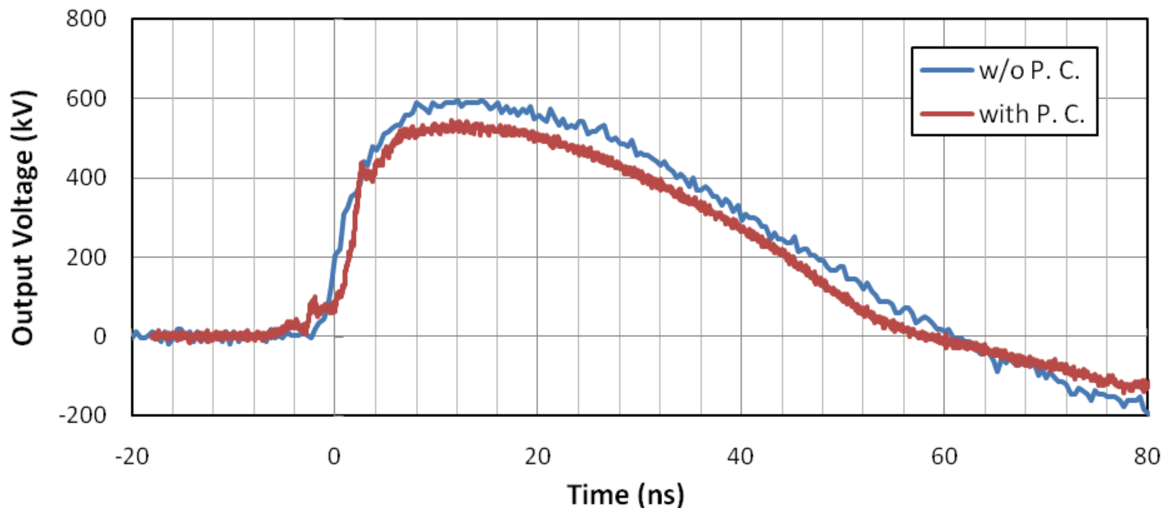

Figure 1. Comparison of two MG40-3C-2700PF Marx generator output waveforms. The blue trace (w/o P. C.) is representative of a Marx generator not equipped with a PCS. The red trace (with P. C.) is representative of a Marx generator equipped with a pulse conditioner to reduce the rise time of the output waveform. Both generators were driving a 41-Ω cable load and were operated at 30-kV charge voltage.

Table 3. Specifications of the MG15-3C-940PF

Parameter	Value	Units
Length	82	cm
Diameter	16.5	cm
Weight	16	kg
Number of Stages	15	--
Erected Voltage (open circuit)	600	kV
Charge Voltage	40	kV
Capacitance per Stage	2.8	nF
Erected Capacitance	188	pF
Source Impedance	52	Ohms

A. Baseline Performance

As with the LM3C, adjustments can also be made to the SM3C to reduce the rise time, but as before, the adjustments typically result in high operating pressures that could cause unsafe operating conditions in deployment scenarios and should be avoided if possible. The SM3C used for testing was operated at ~ 85 psi at a charge voltage of 30 kV and is representative of an SM3C operated under normal conditions. The measured output pulse, shown in blue in Figure 2, had a FWHM of 23.3 ns with a 10-90 rise time of 6.2 ns and a 20-80 rise time of 3.65 ns. Another metric, the 10-70 rise time as defined by the difference in time between when the pulse first reaches 70 percent of its peak amplitude and when the pulse first reaches 10 percent of its peak amplitude, more accurately depicts the reduction in rise time realized by the PCS described later. The 10-70 rise time observed for the standard SM3C was 3.2 ns. The cable load used for the LM3C testing was also used for testing the SM3C.

B. Pulse Conditioning

A custom housing was manufactured as a test stand for a variety of different PCSs and was 8 inches longer than the standard SM3C housing length. This additional volume provided more than ample space for peaking circuit integration. The best result achieved with the integrated peaking circuit, shown in red in Figure 2, was a FWHM of 23.4 ns with a 10-90 rise time of 3.65 ns and a 20-80 rise time of 2.9 ns. The 10-90 rise time was reduced over the traditionally configured Marx generator by 40% while the 20-80 rise time did not show significant improvement. The 10-70 rise time of 1.48 ns showed dramatic improvement over the traditionally configured Marx and was reduced to 50% of the original value. As with the LM3C, electrostatic simulations and measurements verified that the stray capacitance across the switch was below 10% of the peaking capacitance for a range of different gap distances.

I. ANALYSIS OF PERFORMANCE

Both peaking circuits perform well considering the physical constraints placed on the systems. The PCSs were placed in the same housing as the Marx generator

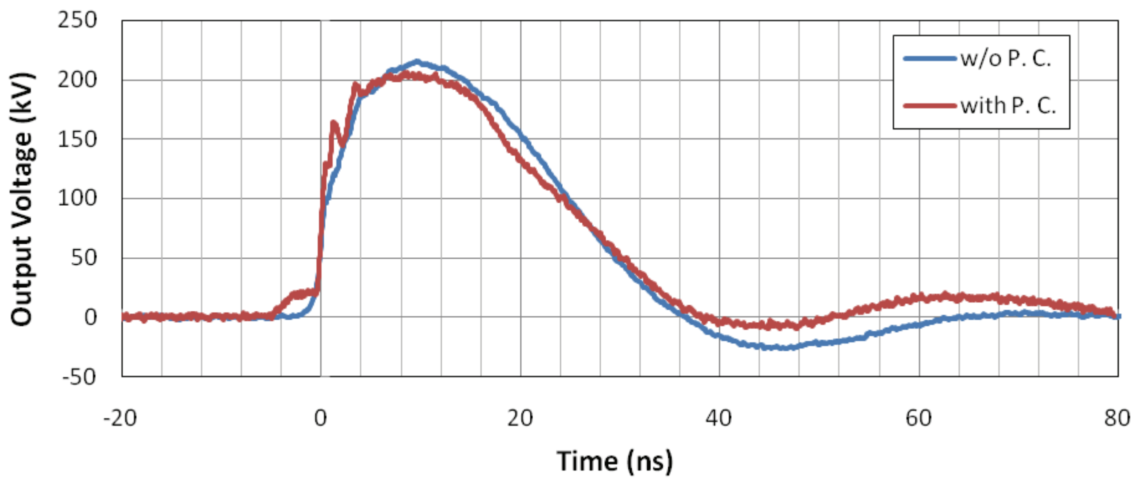

Figure 2. Comparison of two MG15-3C-940PF Marx generator output waveforms. The blue trace (w/o P. C.) is representative of a Marx generator not equipped with a PCS. The red trace (with P. C.) is representative of a Marx generator equipped with a pulse conditioner to reduce the rise time of the output waveform. Both generators were driving a 41-Ω cable load and were operated at 30-kV charge voltage.

which immediately constrained their outer diameter and, in one case, the overall length. The desire to pressurize the peaking circuit volume independently of the Marx housing volume further constrained the PCSs, and when coupled with the mechanical design of each of the systems, limited the maximum pressure achievable in the switch volume to 100 psi above the Marx housing pressure.

A rough analysis was performed to determine which phase of switching was limiting the rise time of the PCS. Through experimentation and simulation it was found that the average electric field across the output switch at the time of closure is approximately 2.0 MV/cm. Using the equation for resistive phase time presented by Charlie Martin in [8], it was found that the plasma formation in this phase occurs in less than 250 ps. Consequently, the inductive time constant appears to be the limiting factor to achieving sub-nanosecond rise times and is probably caused by the geometric inductance present in the Marx output transition to the coaxial load cable. APELC is presently working on PCSs that are independently housed in order to achieve higher working pressures within the output switch volume as well as redesigning a transition to an output cable within to reduce the inductive time constant.

II. CONCLUSIONS

APELC has designed, developed, and fielded PCSs that reduce Marx generator rise times by up to 50%. Further development is planned and it is believed that the transition from the final stage of the Marx generator to the coaxial load cable is limiting the achievable rise times.

III. REFERENCES

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