DEVELOPMENT OF A DUAL-POLARITY MARX GENERATOR DESIGNED FOR PULSE CHARGING A DIPOLE ANTENNA

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Abstract

Dipole antennas have recently seen a lot of use for the generation of high-power, wideband RF. Typically, a single-ended pulse generator, such as a Marx generator or a Vector Inversion Generator (VIG) pulse charges a dipole, which has an integrated resonator. Once charged, the resonator switches and the cyclic energy is dissipated by the dipole geometry. There is a desire to increase the radiated field strengths of these devices, which requires larger pulse charge voltages.

Applied Physical Electronics, L.C. (APELC) has been developing a dual-polarity Marx generator for pulse charging the dipole with a double ended, or a balanced source, hoping to achieve greater efficiencies in the radiated electric field. The APELC generator is capable of delivering +/- 300 kV pulses onto 50-Ohm coaxial cables, with low temporal jitter. This paper discusses the design of the generator, as well as experimental results. Included, is a comparison of the dipole radiation when sourced by a single ended charge versus a double ended charge.

INTRODUCTION

Wideband RF sources are relatively simple first order devices. A simple resonator circuit, or even a quarter wave transmission line, can be built into a dipole geometry. Once charge to a desired voltage, the resonator switches and begins filling the dipole structure with a surface current related to the frequency of the resonator. The electric field radiated by the dipole is given by

$$E(r) \;=\; \sqrt{\frac{P_{ant}}{4\pi r^2}\; x \; G \; x \; 377} \qquad (1)$$

Where r is the range from the antenna, P_{ant} is the power on the antenna and G is the antenna gain. Since the dipole is approximately a 2 dB structure, the only parameter available to increase the radiated field strength is the power on the antenna. Typical thin wire dipole antennas have a nominal impedance of 75 ohms. By increasing the diameter of the dipole's arms, commonly referred to as a "fat" dipole, the impedance can be decreased, which of course increases the device's power. However, there is a diminishing return on the radiated field strength with increased dipole diameter, as the dipole begins to look like a point source. Instead, the voltage placed on the fat dipole should be increased, thereby maximizing the power on the antenna.

To obtain very high voltages, the dipole should be pulse charged with a high voltage, fast rising impulse source, such as a Marx generator or a VIG, and with the goal of charging the dipole to extreme voltages before the resonator switches. Achieving extreme voltage requires fast risetime pulses, on the order of a few ns. Marx generators are very capable of this performance, showing the ability to deliver several hundred kV with ns risetimes. While VIGs can bring higher repetition rates than the Marx generators, they also bring slower risetimes and lower operating voltages.

The connection between the dipole and the pulse generator is also problematic. Some developers simply use a two wire method, which results in a large loop, thereby slowing the risetime of the pulse charge voltage, and ultimately reducing the peak charge voltage on the resonator. Connecting the pulse generator to the antenna, via coaxial cable reduces the loop inductance at the antenna; however, it complicates the problem, as the pulse generator will necessarily drive the 50 Ohm cable impedance, which in turn, is capacitively loaded by the resonator.

So, as the voltage of the pulse generator is increased, there is the constant challenge of trying to match to the 50 Ohm cable, and this leads to inefficiencies due to larger capacitance of the pulse generator.

This paper describes an alternative method, one in which two sources deliver opposite-polarity high voltage pulses to charge the dipole antenna. As a result two smaller sources, each matching to a 50 ohm cable, simultaneously deliver their energy to a common antenna load, and thus resulting in a differential doubled voltage. And since the dipole is a capacitive load, and resonant charging conditions exist, a pulse charge of up to four times the voltage of a single Marx generator can be obtained.

The critical feature in this approach is delivering the two opposite polarity pulses simultaneously, or with a minimized temporal jitter so that a maximum voltage differential will be realized on the antenna.

BACKGROUND

Wideband sources are simple and cheap, and can be very effective in defeating electronically-controlled threats. Diehl has led the development, with their DS-110 "Compact RF Source."[1] A number of programs, including efforts by APELC, have developed similar

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sources, achieving similar results.[2,3] In general, damped sinusoidal signals (several cycles) are radiated with center frequencies from a few 10's of MHz to more than 500 MHz and electric field strengths from 50 to 300 kV/m (at 1 m). Achieving higher electric field strengths is difficult. Larger pulsed-power sources are required, and antenna breakdown becomes a concern.

APELC conducted an analysis, followed by an experiment, to test the electric-field yield versus applied voltage for a 400 MHz dipole. An analysis was made to determine the best method for putting higher voltages onto the dipole antenna, including the use of larger Marx generators and dual polarity Marx generators.

APELC's traditional approach to driving the resonator/dipole is in Figure 1. A maximum voltage of 300 kV is launched onto the cable, from a 600 kV erected voltage and into a matched 50 Ohm load. A possible 600 kV charge can be realized on the dipole, assuming that the peak resonant charge can be achieved before the resonator switches.

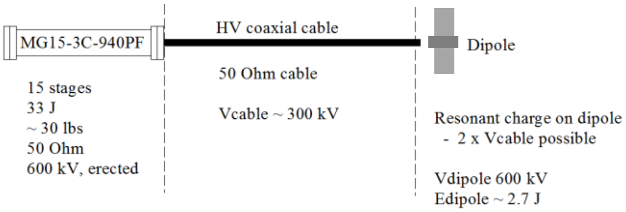

Figure 1. APELC's simple dipole geometry, in which a Marx generator pulse charges a simple dipole via high voltage coaxial cable.

To increase the pulse charge voltage on the dipole, the erected voltage of the Marx generator must be increased, which means adding more stages to the generator. Unfortunately, simply adding stages will not linearly translate into a similar added voltage on the load, since the impedance of the coaxial cable plays an important role. In fact, there is a diminishing return to adding identical stages to a Marx generator.

The equation below provides a first order of magnitude calculation of the impedance of the generator. To double the erected voltage, the number of stages is double from the geometry of the single Marx generator.

$$Z_{Marx} = \sqrt{\frac{L_{Marx}}{C_{Marx}}} = \sqrt{\frac{2\,L_{single\,Marx}}{\frac{C_{single\,Marx}}{2}}} = 2\sqrt{\frac{L_{single\,Marx}}{C_{single\,Marx}}} \qquad (1)$$

where

$$C_{single\ Marx} = C_{erected} = \frac{C_{stage}}{N} \qquad (2)$$

and

$$L_{single\ Marx} = L_{erected} = L_{stage}\ x\ N \qquad (3)$$

and N equals the number of stages.

So, for the case in which the single Marx generator is simply doubled in its number of stages, resulting in a 30 stage, 100 Ohm generator capable of erecting 1.2 MV and delivery 66 J per pulse. However, as described in Figure 2, only 400 kV is actually delivered onto the cable, or up to 800 kV on the load, assuming a full resonant charge on the dipole. More concerning is the energy efficiency. The generator described in Figure 2 delivers 66 J; however, with an optimistic 800 kV on the dipole, only 4.8 J is transferred, with the remaining amount being dissipated by the Marx generator. This inefficiency will reduce the maximum repetition rate, and lifetime of the system.

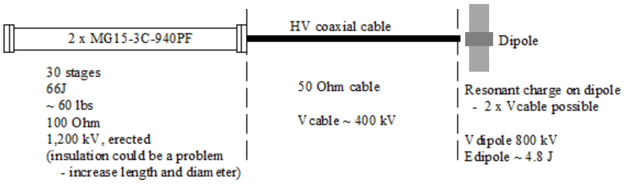

Figure 2. An illustration of the single Marx generator being doubled in the number of stages to drive a coaxial cable-connected dipole antenna.

The typical pulse power approach to achieve more voltage on the cable is to simply increase the erected capacitance of the Marx generator to better match to the 50 Ohm cable. To develop a 50 Ohm generator, with an erected voltage of 1.2 MV, a 30 stage design is required, with four times the capacitance, which results in an energy store of 216 J. As described in Figure 3, a 600 kV pulse will be launched onto the cable, and assuming that a maximized resonant charge of the dipole results in a 1.2 MV charge, the dipole will store approximately 10.8 J, which means that the Marx generator must dissipate more than 200 J per shot.

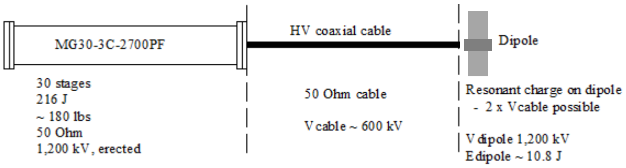

Figure 3. An illustration of Marx generator designed to match the 50 Ohm cable driving a coaxial cable-connected dipole antenna.

It quickly becomes apparent that the traditional approach is not correct. Ideally, a lightweight 30 stage Marx generator, with low energy store and a 50 Ohm impedance should be developed. One method might include an intermediate pulse conditioning element to compress the Marx pulse, will increasing the amplitude of the voltage pulse launched onto the coaxial cable. However, high speed pulse compression is very difficult. A dual polarity Marx generator is posed as an alternative solution, and is the basis for this paper. Since the single Marx generator is a very good match to the coaxial cable, tow generators, one generator for each charge polarity, combining their pulses at the load, could result in a differential pulse charge voltage of twice the resonant charge of the single Marx generator.

For this effort, APELC's MG15-3C-940PF Marx generator is used. As described in Figure 4, two generators are connected at their inputs and erect away from each other, with each delivering a pulse magnitude of 300 kV onto their respective high voltage coaxial cables. The cables rejoin at the dipole antenna to deliver the differential charge, to produce an assumed resonant charge of 1.2 MV. The primary benefit of this configuration is that the dual polarity geometry delivers a maximum combined energy of 66 J, instead of the 210 J of the previous example.

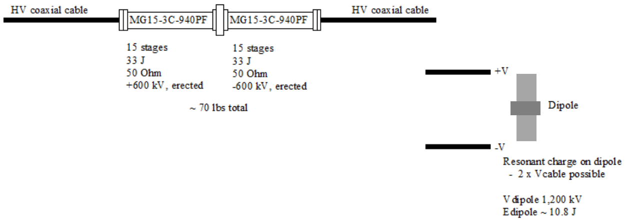

Figure 4. An illustration of a dual polarity Marx generator driving a dipole antenna.

The major concern with this approach is the temporal jitter between the two pulses delivered to the dipole. For maximum performance, the pulses should arrive simultaneously, or with low jitter, as described in Figure 5, so that the maximum different pulse charge potential is realized across the load. Pulses arriving with a high temporal jitter, also described in Figure 5, will result in the poor performance of the dipole antenna, since the resonator will likely switch before the second pulse has arrived.

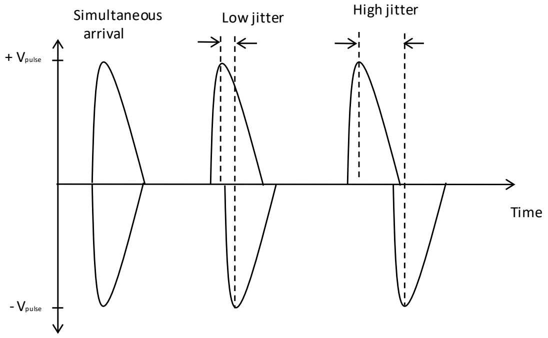

Figure 5. Description of temporal jitter with dual polarity pulses.

APELC has previously determined that approximately 90% the jitter in a wave-erection Marx generator is located in the first spark gap (or trigger gap). So, if the two generators share a common trigger gap, the jitter between their outputs should be minimized. [3]

EXPERIMENTAL ARRANGEMENT

An experimental system was designed using two APELC Marx generators (model MG15-3C-940PF). Each Marx generator has been designed to erect 600 kV and store 33 J, from a maximum charge voltage of 40 kV. The generator delivers an approximate 20 ns FWHM pulse, with a risetime of approximately 2 – 3 ns. The generator matches well to a 50 Ohm high voltage coaxial cable. Table 1 provides the basic electrical parameters for the base Marx generator.

Table 1. Individual generator parameters

Parameter	Description	Value	Unit
V_{ch}	Maximum charge voltage	30	kV
N	Number of stages	15	
C_{st}	Capacitance per stage	940	pF
L_{st}	Inductance per stage	15	nH
C_{erect}	Erected capacitance	63	pF
L_{series}	Approximate series erected inductance	225	nH
Z_{marx}	Approximate Marx impedance	60	Ω
V_{erect}	Erected voltage	450	
V_{load}	Voltage on a 50 Ohm cable	205	kV
E_{marx}	Energy per pulse	6.345	J
P_{paek}	Peak power on 50 Ohm cable	838	MW

A photograph of the prototype system is provided in Figure 6. The two Marx generators are joined to share a common input interface, which provides the feed-throughs for both power supplies, the trigger connection and the port for pressurize dry air. Each generator is loaded by a high voltage coaxial cable.

Figure 6. Experimental prototype dual polarity Marx generator source.

In order to achieve low jitter between the two Marx generators, a patented common trigger gap was implemented.[4] The trigger gap is a simple three electrode field distortion triggered spark gap. The positively-charged Marx generator is connected to one of the main electrodes. The negatively-charge Marx generator is connected to the opposite main electrode, and the field distortion element is floated at a zero potential and centered between the two main electrodes, so that the field between the two main electrodes is not distorted. Delivering a high voltage pulse to the trigger pin element dramatically distorts the field, and results in the arcing between the primary electrodes, with very low temporal jitter. The two Marx generators then erect away from the center section, and launch their pulses onto their respective output coaxial cables.

The dual polarity Marx generator was tested as shown in Figure 7. Two high voltage DC power supplies were used to source the generators; and a single APELC-made trigger unit was used to trigger the common trigger gap. Inline Current Viewing Resistors (CVRs) were mounted on each output coaxial cable, and monitored with a Tektronix TDS 5803 (8 GHz, real-time) oscilloscope.

For the initial testing, both output cables were resistively loaded.

The oscilloscope was triggered on channel 1 by the signal from the CVR located on the positively-charge generator. The CVR located on the negatively-charged generator was connected to channel 2 on the oscilloscope.

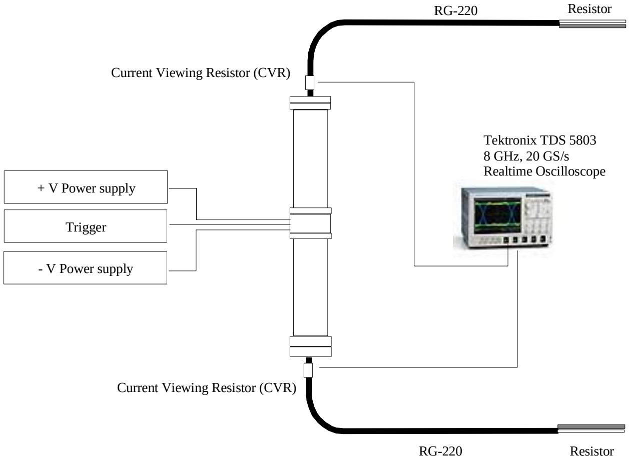

Figure 7. Experimental arrangement for testing the prototype dual polarity Marx generator source.

EXPERIMENTAL RESULTS

The jitter measurements were made from 10-shot series and captured using Tektronix's FastFrame™ feature. The pulses are then manually analyzed for their time to cross a defined voltage threshold, and the standard deviation of the resulting data series was then calculated.

The reliability of the trigger signal was first determined by measuring its jitter. A zoomed view of the trigger signals is provided in Figure 8. A voltage threshold of equal to "1" was chosen, and a standard deviation of 38.7 ps was calculated. This seems relatively high, since the oscilloscope is triggered from the measurement signal. This is likely due to the fact that the sampling rate was somewhat low, with 50 ps between data points.

Figure 9 provides a sample of the measured signal from the negatively-charged generator from a FastFrame™ capture off channel 2; and Figure 10 provides a zoomed overlay of the pulses for comparison. The Marx generators were charged to ±15 kV. A voltage threshold of 1 V resulted in a range, or spread, from 940 ps to 985 ps, with a calculated jitter of 120 ps.

The charge voltage of the generators was then increased to ± 30 kV. Figure 12 provides the overlay of pulses from the 10 shot series, and a voltage threshold of 2.5 V was chosen. The spread was measured from 620 ps to 675 ps, with a calculated jitter of 174 ps.

Finally, the charge voltage was increased to ± 40 kV, and a threshold voltage of 2.5 was again chosen. Figure 13 provides the overlay of pulses from the 10 shot sequence. The temporal spread was from 5.35 ns to 6.65 ns, with a calculated jitter of 432 ps.

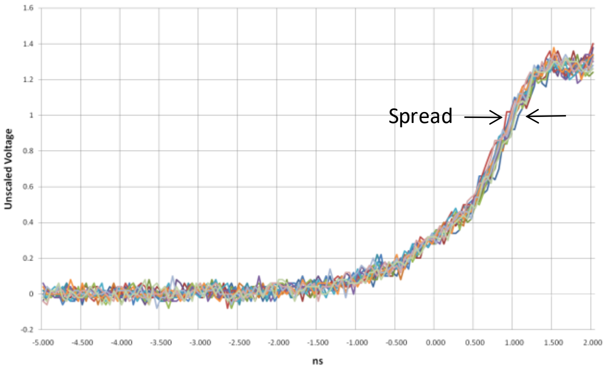

Figure 8. An overlay of the 10 waveforms from the trigger signal.

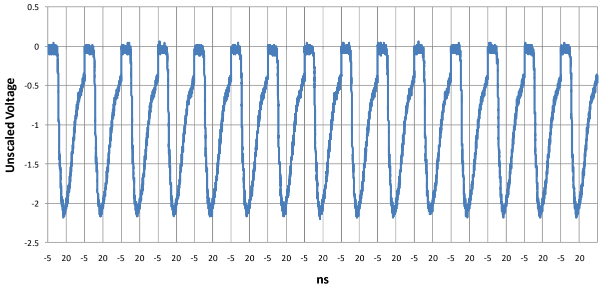

Figure 9. A 10-shot sequence captured from the negatively-charge Marx generator charged to 15 kV.

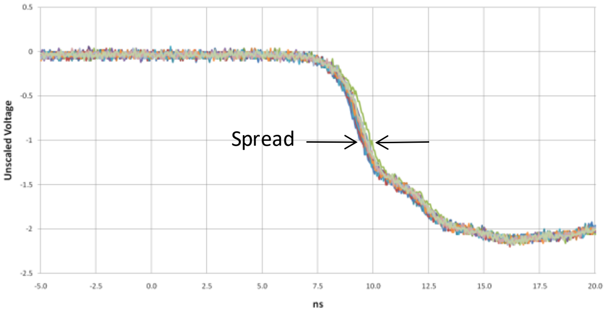

Figure 10. A zoomed and overlayed view of the 10-shot sequence of pulses measured from the negatively-charged Marx generator from the ±15 kV charge test.

Ultimately, the system's utility is measured by the increased performance on the dipole antenna. Figure 13 provides a radiated waveform measured from a 400 MHz dipole antenna pulse charged by the configuration described in Figure 1. The radiated field produced by this configuration was approximately 200 kV/m, normalized to 1 m.

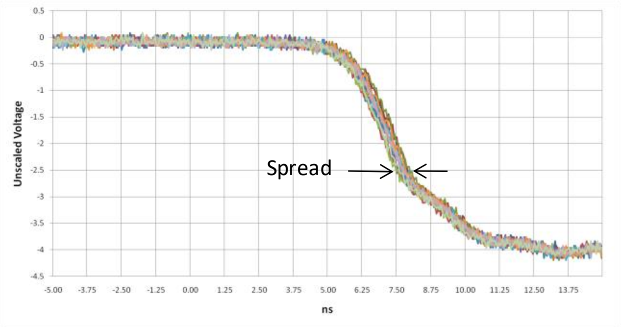

Figure 11. A zoomed and overlayed view of the 10-shot sequence of pulses measured from the negatively-charged Marx generator from the ±30 kV charge test.

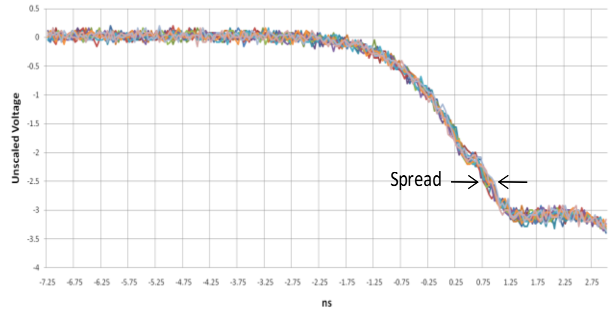

Figure 12. A zoomed and overlayed view of the 10-shot sequence of pulses measured from the negatively-charged Marx generator from the ±40 kV charge test.

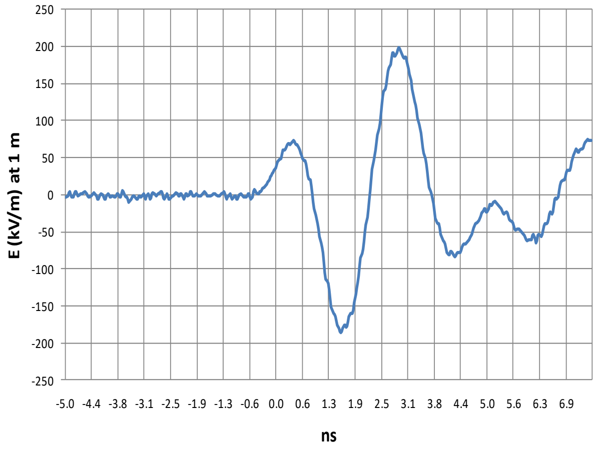

Figure 13. A measured signal radiated from a 400 MHz dipole antenna driven by a single 600 kV Marx generator.

The same antenna was driven by the prototype dual polarity Marx generator source, discussed in this paper. A sample waveform is provided in Figure 14, demonstrating the ability to generate a radiated electric field strength of 385 kV/m (at 1 m) from a single antenna element. As hoped, the field strength increased linearly with the scaling of the Marx generator, from 200 kV/m when sourced by a 600 kV generator, to nearly 400 kV/m when sourced by a 600 kV generator.

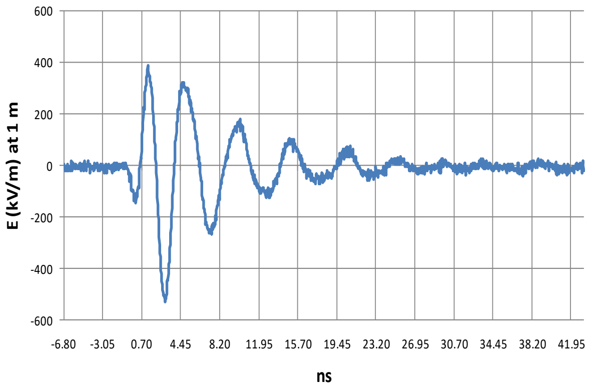

Figure 14. A measured signal from the 400 MHz dipole antenna driven by the dual polarity 1.2 MV Marx generator.

SUMMARY

The development of a prototype dual polarity Marx generator has been very successful. We were able to easily meet the jitter technical milestone of sub-2 ns. The worse jitter measurements came with the 40 kV shots; however the jitter remained well below 500 ps. It is interesting that the jitter increased as we increased the charge voltage from ±15 kV to ±40 kV. We expected the opposite situation, with the jitter decreasing as the field strength on the gaps was increased. To date, we do not have an explanation for this behavior.

When attaching the dipole as the load element, the 400-kV/m milestone was missed by 16 kV/m. We do believe the 400 kV/m is achievable. In fact, with a backing reflector, electric field strengths in excess of 500 kV are achievable.

Future work will be focused toward stabilizing the triggering, and preventing self breakdown, or un-triggered event from occurring. Additional work will be made toward altering the packaging and maximizing the dipole performance.

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[4] *Method and Apparatus for Generating Short Duration High Voltage Energy Pulses Using Integrated Generators and Antennae*, U.S. Patent number 7,345,382 B2.

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