The Generation of High Electric Field Strength RF Energy Using Marx Generators

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Abstract

The Wave Erection Marx Generator is proving to be an excellent high voltage source for the direct generation of RF energy. Unfortunately, effectively radiating the impulse energy is challenging, both in efficiency and high voltage-holdoff capability. Successful efforts have been made to generate RF energy in both the Narrow Band and Ultra Wideband realm, with field strengths in excess of 1 kV/m at 100 m achieved. This paper briefly describes the impulse generator and explores its use for generating Narrow Band RF energy as well as Ultra Wideband energy. Experimental results will be presented.

I. INTRODUCTION

Compact Marx generators have been employed for many years as trigger generators for larger systems. These generators are typically designed with pulse characteristics of more than 200 kV in peak voltage, 3 – 4 ns rise times, 1 – 3 ns rms jitter and pulse widths of 10's of ns. Unfortunately, these characteristics make the compact Marx generator an impractical source for directly generating RF energy by driving an antenna due to the slow rise time.

However, recent efforts [1] with compact Marx generators have brought faster rise times, higher peak voltages, and extremely low jitter values, making them viable candidates for compact Ultra Wideband (UWB) sources for both single and multiple generator systems.

While efforts continue the successful development of these generators, deployability will be limited by compact, high voltage, impulse radiating antennas. Typical impulse antennas with any respectable amount of gain and directivity are large and cumbersome. Furthermore, high voltage antennas capable of handling voltages in excess of 100 kV are simply not available.

This paper discusses two types of impulse antennas sourced by the APELC impulse Marx generator. A linear half TEM horn antenna is demonstrated for the generation of Ultra WideBand signals and a spiral antenna is demonstrated for the generation of Narrow Band radiation. The Marx generators under development by APELC are capable of delivering voltages in excess of 400 kV. The primary goal with these antennas is to efficiently radiate the impulse to achieve extremely intense electric fields. Each antenna is discussed in its design and experimental performance.

II. BACKGROUND

A. The Wave Erection Marx Generator

The most efficient, compact and economical method of generating a repetitive, large magnitude, electromagnetic impulse is the wave erection of a spark gap-switched Marx circuit. Wave erection is necessary to obtain the fast voltage rise times from the Marx circuit that generates the ultra-wideband frequencies necessary for high resolution radar or the interdiction of flight controls and computer memories for electronic warfare. Wave erection is made possible through the proper design of the stray capacitance and the inter-stage capacitance, in concert with coupling the spark gaps via ultra-violet energy. This results in a sub-ns rise time for output voltages of several hundred kV at low per pulse energies.

A 17-stage Marx generator based on the wave-erection principle is fabricated for the antenna testing. This generator is designed to deliver more than 360 kV into a 50 Ω load; however, for the purpose of preliminary antenna measurements, it is operated with a peak voltage of 170 kV, and a rise time of approximately 250 ps, as measured with a current-viewing resistor and shown in Figure 1.

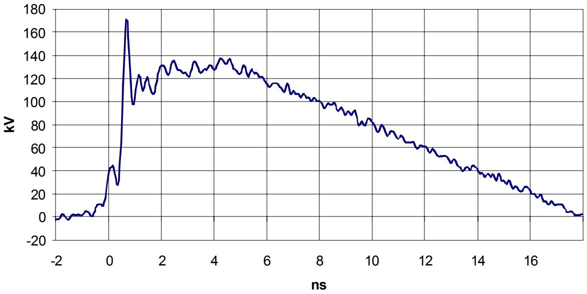

Figure 1. Output waveform from the Marx generator.

B. Impulse Antennas

Several antenna designs are pursued including a linear half TEM horn and a spiral antenna. The initial focus is to gain an understanding of pulsed high voltage antenna characteristics, and to establish antenna baseline parameters for gain, radiation pattern, optimal impedance transformation requirements, and field polarization over the frequencies of interest. Future designs will build on these results.

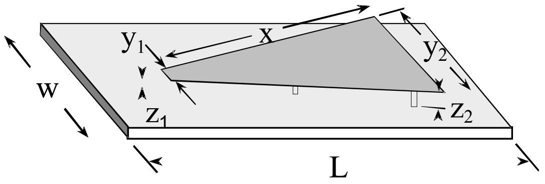

Figure 2. Geometry of the linear half TEM horn antenna.

The linear half TEM-styled horn antenna is illustrated in Figure 2. This antenna is characterized by a single TEM plane extending over a large ground plane. The TEM plane linearly expands in both the E and H directions as the wave propagates toward the output. As a result, the characteristic impedance should linearly expand from the 50 Ω input impedance to the 377 Ω characteristic impedance of free space.

The basic transmission line equation for a parallel plate line is used for the design; however, since the antenna is to be operated at very high voltages, the input portion of the antenna has an insulator other than air. As the wave propagates toward the output, the insulator tapers to a zero thickness. Thus, at the input, the width of the TEM plate is defined as

$$w = h\frac{377}{Z_o\,\varepsilon_r^{1/2} - 2}. \tag{1}$$

This dimension determines the high frequency cutoff for the antenna. However, the additional parameter of high voltage hold-off must be considered. While a small plate separation may allow for the radiation of higher frequency terms, failure of the antenna may result from too little insulating material.

The characteristic impedance of the output end of the TEM plate is defined by

$$w = h\frac{377}{Z_o\,\varepsilon_r^{1/2}}. \tag{2}$$

This dimension is chosen to match the impedance of free space and also defines the low frequency cut-off of the antenna.

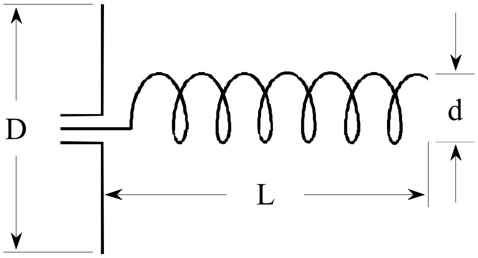

Figure 3. The spiral antenna.

Spiral antennas offer more control over the radiated frequency. These antennas offer bandwidths of 2:1, and up to 5:1 are possible. They are unidirectional and are circularly polarized. As illustrated in Figure 3, once the center conductor parts from the ground plane, it spirals around an imaginary cylinder whose circumference is approximately one wavelength in diameter. Choosing the number of coils, which defines the gain, the length, L is derived from a coil spacing definition of $\lambda \sin \theta$, where θ is typically 12 – 14 degrees. The minimum ground plane diameter is ¾ λ.

III. EXPERIMENTAL ARRANGEMENT

A. Antennas

The antennas described in the *Background* section of this paper are fabricated for a first-pass analysis, since only baseline parameters and characteristics are sought.

The linear half-TEM antenna is designed for a frequency spectrum of more than 2 GHz to 500 MHz. The lower frequency cutoff is chosen for antenna compactness.

The input connection is designed for easy connection to the RG-220 cable. The cable connection is orthogonal to the wave propagation; however, the insulating material of the feed connection continues between the plates in the direction of the wave propagation to minimize premature breakdown.

Design of the input plate separation begins with the high frequency cut-off point. In the case of the experimental Marx generator, this is 214 mm, which would result in a large reflection point. However, the insulating material of RG-220 is approximately 8.5 mm. Therefore, a plate separation of 8 mm is chosen to minimize unwanted reflects while maintaining high frequency content. Also note that using acrylic for the insulating material, a theoretical 125 kV can be applied before breakdown occurs. Using equation (1), the plate width is derived to be approximately 40 mm.

The plate separation at the output is chosen at a nominal 290 mm. The width of the plate is derived from equation (2). The following dimensions, as defined by Figure 2 result.

$w = 600$ mm	$L = 1220$ mm
$x = 910$ mm	
$y_1 = 40$ mm	$y_2 = 290$ mm
$z_1 = 8$ mm	$z_2 = 290$ mm

The spiral antenna, like the half-TEM ground plane antenna, is fabricated for easy connection with the RG-220 cable. The antenna is designed for an operating frequency of 1 GHz and 10 turns. Therefore, the coil diameter, d, is set at 95 mm, with a length, L, of 770 mm. The ground plane diameter. D, is chosen at 230 mm.

B. Test Range

The antennas are range tested in an open field with a configuration illustrated in Figure 4. The antennas are separated by 100 m and elevated to a height of 10 m to delay the effects of ground bounce for approximately 7 ns. A receiving probe was purchased from Farr Research [2] (model number FRI-TEM-2-50) and feeds a Tektronix TDS 694C oscilloscope (3 GHz, 10 GS/s).

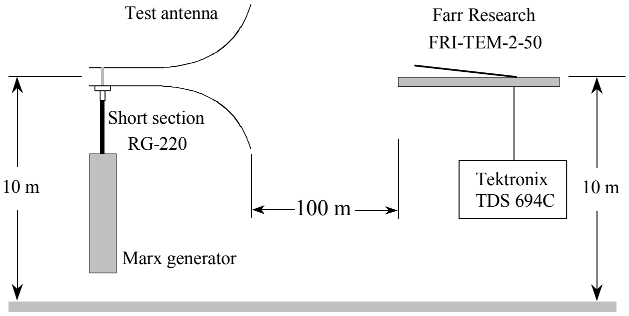

Figure 4. Test range illustration.

IV. EXPERIMENTAL RESULTS

The linear half-TEM horn antenna is driven by the experimental Marx generator, resulting in the measured waveform shown in Figure 5. A very nearly monopulse results with an electric field of approximately 1100 V/m at 100 m. The pulse is characterized by the Marx generator's 250 ps rise time and has an impulse width of less than 300 ps, FWHM. Also note in Figure 5 the ground bounce signal following 7 ns from the original signal.

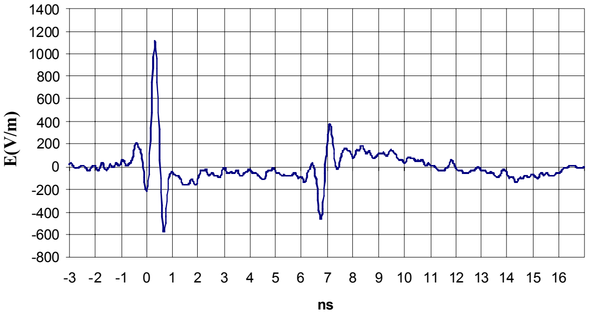

Figure 5. Radiated signal from the linear half TEM.

The Fourier spectrum resulting from the monopulse waveform is shown in Figure 6. As expected, the majority of the signal energy resides in the lower frequencies, from approximately 1 GHz down through 100 MHz. Not realized in this depiction is the energy lost, or attenuated by the antenna, since the low frequency cut-off is approximately 500 MHz. Future efforts will quantize the energy lost, as well as analyzing the trade-off between attenuation and the geometry compactness that lead to the design of a smaller antenna.

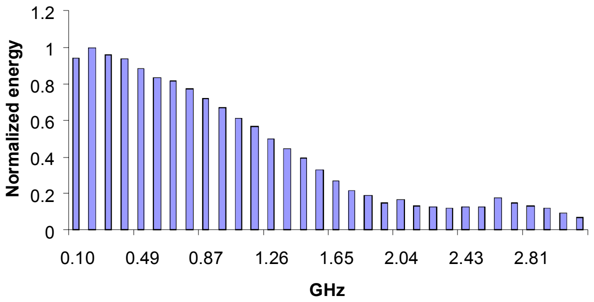

Figure 6. The normalized FFT of the linear half-TEM.

To gain some knowledge of the antennas performance beyond field strength measurements, simple Time Domain Reflectometry (TDR) measurements are made. As shown in Figure 7 a Tektronix 11801C sampling oscilloscope with an SD-24 module is used for the TDR measurement. A 2 m section of RG-220 is fitted with an SMA connector for connection to the oscilloscope, while the opposite end fits the customized antenna interconnection.

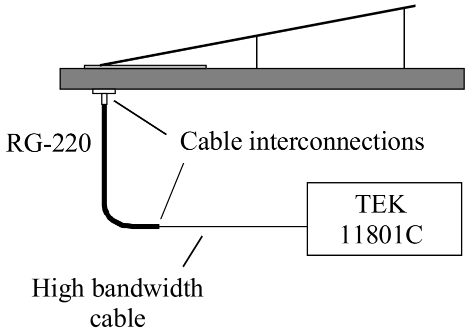

Figure 7. TDR measurement configuration.

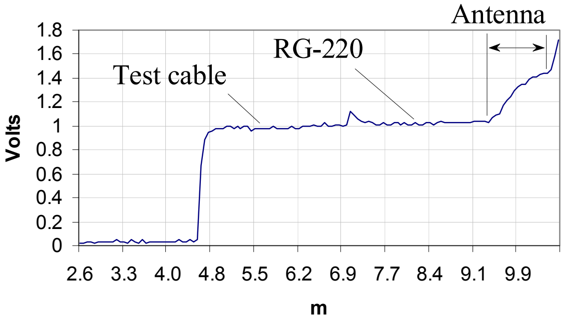

Figure 8. The TDR measurement of the linear half TEM.

The TDR measurement for the linear half TEM horn is shown in Figure 8. The TDR trace shows the somewhat linear impedance gradient of the antenna. The points of interest include the RG-220 cable, the interconnection between the antenna and the RG-220, the insulator at the input of the cable as well as the TEM plate itself. The RG-220 appears to be somewhat noisy, varying in impedance by several Ohms as the wave propagates the cable. The interconnection between the RG-220 and the antenna appears inductive, as anticipated, due to the orthogonal transition. The transition from the acrylic spacer is apparent and should be made more gradual in future designs.

Figure 9 provides the measured radiation waveform of the coil antenna sourced by the Marx generator. As shown, several cycles of energy are delivered at approximately 1 GHz. Both vertical and horizontal polarization measurements were made, with each revealing an electric field of approximately 300 V/m at 100 m. Figure 10 provides the normalized Fourier spectrum, revealing that a narrow band of energy was radiated.

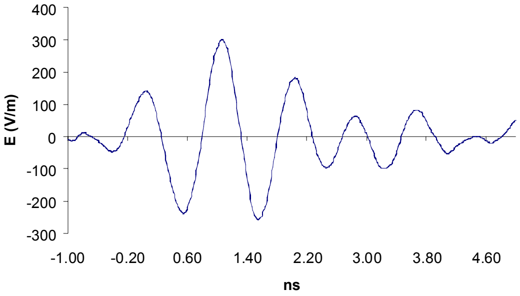

Figure 9. Radiated signal from the 1 GHz coil.

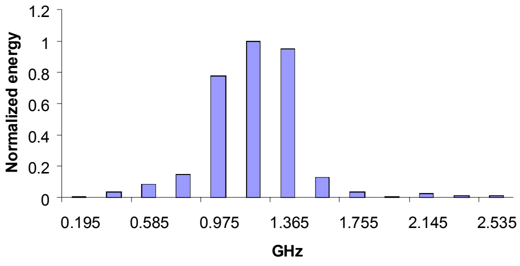

Figure 10. The normalized FFT of the 1 GHz coil.

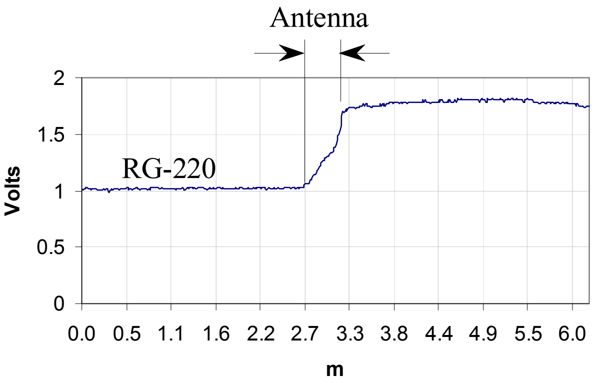

Figure 11. The TDR measurement of the 1 GHz coil.

The TDR measurement results of the 1 GHz coil antenna are shown in Figure 11. In this case, the transition from the RG-220 and the antenna is more uniform, likely due to the fact that the coil's conductor is very similar in size and shape to that of the RG-220's center conductor. The TDR results also seem to indicate that the impedance gradient from 50 Ω to 377 Ω is quick. Also noted is the rate change in the impedance that appears between the first and second coil. Future efforts will work toward correlating the rate of change in the impedance to the measured field strength.

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V. CONCLUSION

This paper has presented preliminary results of two types of antennas matched to the APELC impulse Marx generator; the linear half TEM horn antenna and a 1 GHz spiral antenna. Ultimately, extreme electric field strengths are desired. As a result, this effort begins identifying candidate antenna configurations capable of operating at 100's of kV in the RF spectrum.

The linear half TEM horn antenna was demonstrated to deliver an electric field strength in excess of 1100 V/m at 100 m. The antenna was capable of radiating frequencies of several 10's GHz; however, the low frequency cut-off was 500 MHz, which resulted in an attenuated signal. Furthermore, the heavily insulated cable interconnection proved to be inefficient, possibly leading to attenuation as well.

The spiral antenna was designed to radiate a 1 GHz signal. The measured response demonstrated an electric field strength of more than 300 V/m in both the vertical and horizontal planes. The cable interconnection proved to be efficient; however, there were concerns with the impedance gradient. Future work will look at reducing the impedance rate of change in the hope of increasing the electric field strength.

VI. REFERENCES

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