MARX GENERATOR DESIGN AND PERFORMANCE

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Abstract

This paper presents a broad overview of Marx generators, ranging from the traditional Marx generator to the wave erection generator. It is specifically written as a brief introduction to key concepts with references tied to each area. Key topics include operating techniques, triggering techniques, switches, repetition rates, jitter, and applications.

I. INTRODUCTION

The term *Marx Generator* describes a unique circuit designed for voltage multiplication. In general, all Marx generators follow the same fundamental operation. However, similarities between Marx systems diverge in their construction and performance characteristics as a function of their application.

Typical applications of the Marx generator has been with pulse charging circuits. In essence, the generator is used as an energy storage element, at relatively low voltages, and when fired, pulse charges a transmission line at a high voltage, with typical applications seen in High Power Microwave, and accelerators. Generators in this role tend to be large, as well as slow devices.

Smaller versions of the Marx generator have filled the role of trigger generator for larger systems. These generators are typically characterized by their low per pulse energies, but with several hundreds of kV. The main attraction to these pulsers lies in their rise times and compact geometries.

Recent work has extended the use of these compact generators into the Ultra WideBand (UWB) genre. With rise times as short as 250 ps, these compact generators are finding their way into UWB radar systems and RF weapon systems and come packages that may be hand held [7].

The Marx circuit, on the solid state level has also found applications in laser systems as Pockel's cell drivers and trigger generators. The "credit card" devices can deliver voltages of 10's of kV, with sub-Joule energies [10].

This paper attempts to provide a broad overview of Marx generators, their fundamental operation, and some perspective on electrical characteristics and associated volumes. Fundamental trigger techniques are presented and include information for low jitter operation. Finally, the wave-erection generator is presented.

II. MARX GENERATOR BASICS

The Marx generator is a capacitive energy storage circuit which is charged to a given voltage level and then quickly discharged, delivering its energy quickly to a load at very high power levels. A typical Marx circuit uses resistors to charge N capacitors in parallel to a voltage V,as shown in Figure 1. When triggered, the first switch voltage drops which increases the voltages across the remaining switches, causing a chain reaction of self-triggering. The capacitors are then momentarily switched into a series configuration, delivering a voltage pulse to the load that is theoretically N x V, depicted in Figure 2. The output switch is present to isolate the load while charging the Marx, and to insure full Marx erection before energy is transferred to the load. The charging resistors grade the output voltage from the charging supply during firing, providing electrical isolation.

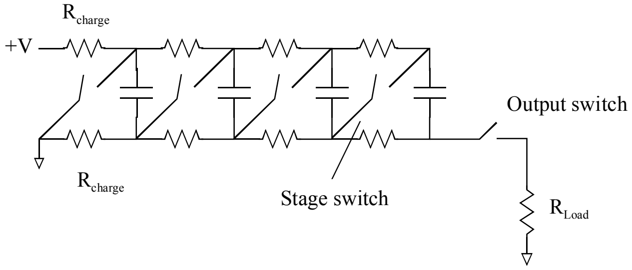


Figure 1. Marx generator charging circuit.

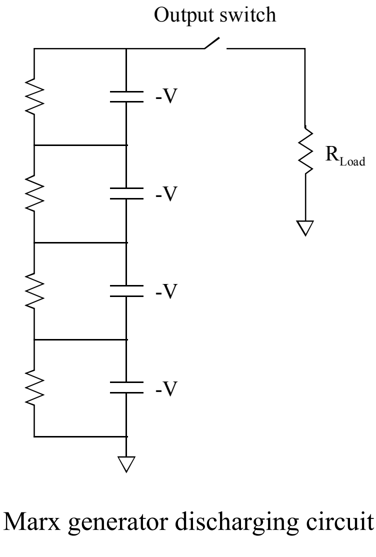


Figure 2. Marx generator discharging circuit.

III. MARX TYPES

In an attempt to categorize the vast genre of Marx generators, this paper chooses Four fundamental types; large, moderate, compact, and solid state Marx generator systems.

A. Large Generators Systems

Large Marx generator systems may be found in the ever-expansive high energy systems such as with the Z-machine and large HPM systems, and often reside in very large rooms. These systems offer Mega-volts and Mega-Joules at relatively long pulse durations. The pulses are slow in their rise time (10's of ns), and due to their massive energy requirements, offer very low repetition rates (essentially single events).

B. Moderate Generator Systems

Moderate Marx generators may be categorized as small room to large desktop-sized systems, offering voltages from 100's of kV to several MV's. Pulse energies may rate into the low MJ's. Pulse widths vary from 10's of ns to μs. Their rise times typically remain slow, on the order of several ns to 10's of ns. However, repetition rates are more achievable and as high as several 10's of Hz.

C. Compact Generator Systems

Compact Marx generators fit into the range of hand-held to desktop-sized systems. These systems over relatively low pulse energies, < 10 J – 1kJ, and high voltages of 100's kV to MV. Fast rise times, 100's ps, are achievable, as well as high repetition rates (> 1 kHz).

D. Solid State Generator Systems

Solid state Marx generators are circuit board size systems with voltages up to the several kV range and less than 1 Joule energy storage. Risetimes in the 100 ps range have been demonstrated. Repetition rates could potentially be in the 10's to 100's of kHz.

Large and moderate Marx generators are typically used as pulse charging sub-systems in larger pulsed power applications. In systems such as Z pinch machines Marx generators are initial energy stores which deliver energy to a pulse compression circuit before reaching the load.

Compact and solid state generators can be designed to have pulse widths that are narrow enough to drive some applications directly. These include ultra wide band antennas, jamming systems, and pulse radar systems. Multi-pulse systems can also be directly driven, with serial temporal signals spaced apart in the 10's of ns for driving a common antenna, or phased array systems with sub-ns jitter and sub-ns phase differences firing into an array of antennas

IV. MARX TRIGGERING TECHNIQUES

The choice of Marx switches is dependent on the operating voltage, pulse repetition frequency, and lifetime, and switching support requirements. Solid state switches may be used in low voltage applications. However, many Marx generators operate in regimes where the only viable alternative is a spark gap.

Spark gap technology is broadly split into liquid filled and gas filled systems. For both cases, the medium provides both the cooling and switching characteristics. Maximum repetition rates are achieved by flowing the medium through the switching region to carry away heat and recover voltage hold-off capability quickly.

Liquid systems typically use oil or water, but can be based on a variety of other liquids. Liquid systems have excellent thermal mitigation properties. However, these systems tend to use pumps and filters to remove contamination, adding to volume and complexity.

Gas systems can be based on a variety of gases, depending on repetition rates, spark gap lifetime, and safety concerns The highest repetition rate systems use high pressure hydrogen due to its ability to recover its insulating properties quickly after firing [4], [5].

V. REPETITION RATE ISSUES

An important parameter for any pulsed power system is the time it requires after firing to recharge and be ready to fire again. Large and moderate generator systems typically have low repetition rates which are dictated by either the power supply's ability to recharge the system or thermal stabilization of the load.

Compact and solid state generator systems obtain size reductions by storing less energy per shot. Typically these systems still have reasonably high peak power levels with narrow pulse widths, so that thermal heating of the system from a single event is low. These systems tend to be operated at higher repetition rates in order to raise the average energy deliver to the load.

High repetition rate systems can still be power supply limited. However, the recovery time of the switches used becomes a key concern

Resistive charging works well for low repetition rates. However, the charging time required by the Marx before firing is approximately equal to $2N^2RC$ and the resistors reduce the charging efficiency. Therefore, for high repetition rate systems the resistors are replaced with inductors to accommodate fast, efficient charging [4], [5].

The addition of mutual coupling between the two inductors associated with a Marx stage can further increase the system performance. For this case, the individual inductances appear smaller during charging and larger during firing, allowing for faster charging with increased firing isolation [6].

VI. MARX DESIGN EXAMPLE

The following example demonstrates key elements of designing a Marx generator for single output pulse delivery into a known real load.

A first order approximation of the Marx generator circuit is a single loop LRC circuit where Leq and Ceq are the lumped inductance and capacitance of the Marx circuit and R is the load resistance. The period of oscillation for an underdamped circuit is given in equation (1) and the Marx impedance in equation (2).

$$T = 2\pi\sqrt{\mathrm{Leq\,Ceq}} \qquad (1)$$

$$Z = \sqrt{\mathrm{Leq/Ceq}} \qquad (2)$$

Critical damping is chosen as a compromise between maximum voltage amplitude and overshoot, as defined by equation 3. For this choice, the FWHM pulse width is about 80% of half the period of underdamped oscillation and that the output voltage will be near 70% of theoretical, shown in equations (4) and (5) where n is the number of stages and Vcharge is the Marx input voltage.

$$Z = R/2 \qquad (3)$$

$$\mathrm{Tpulse} = 0.8\,\pi\sqrt{\mathrm{Leq\,Ceq}} \qquad (4)$$

$$\mathrm{Vout} = 0.7\left(\mathrm{n\ Vcharge}\right) \qquad (5)$$

Therefore, a first pass Marx design is obtained in the following way:

1. Choose the desired Tpulse, Vout, and R.
2. Solve equations (2), (3), and (4) to find Leq and Ceq.
3. Choose n and Vcharge to satisfy equation (5).
4. Calculate the stage inductances and capacitances according to equations (6) and (7).

$$\mathrm{Lstage} = \mathrm{Leq/n} \qquad (6)$$

$$\mathrm{Cstage} = \mathrm{n\,Ceq} \qquad (7)$$

It should be noted that the additional inductance associated with both ends of the Marx has been neglected. They can be easily included by subtracting them from Leq before calculating Lstage. This simplification has been made to more easily show the results of adding stages in the following paragraphs.

Consider the design of a Marx generator with a FWHM pulse width of 8ns with an amplitude of -170kV into 50 Ohms. These require Leq = 80nH and Ceq = 127pF. A charge voltage of 240kV is required, so an 8 stage Marx is chosen with 30 kV charging. The simulated result is shown in Figure 3. The design process shown has been straightforward, and a Marx designed as described typically performs reasonably close to specifications.

It is now assumed that a Marx has been designed and constructed as described. The system works as planned, but now it is decided to increase the output voltage. It seems reasonable to construct more stages just like are presently in use and lengthen the Marx.

How will these additional equivalent stages affect circuit performance, other than changing the charging time? Equation 8, derived from 2, 6 and 7 shows that the impedance of the Marx increases with n. Figure 4 illustrates that the LRC circuit model becomes increasingly underdamped. The pulse length does not change significantly, but more energy is lost in the overshoot, decreasing the voltage efficiency as shown in Figure 5.

$$Z = n\sqrt{\mathrm{Lstage/Cstage}} \qquad (8)$$

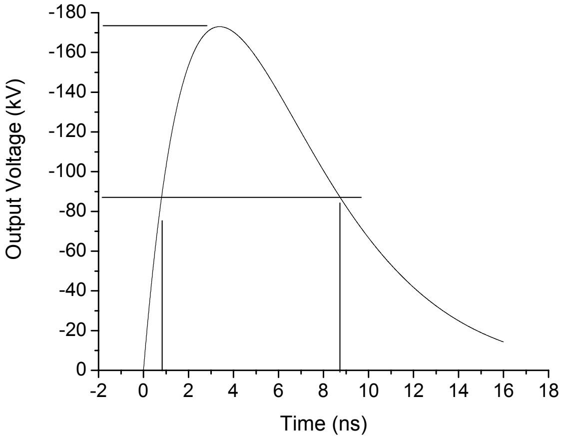


Figure 3. Simulation Marx generator design example.

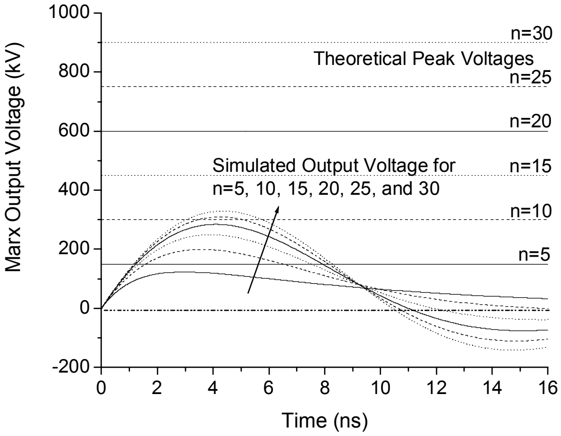
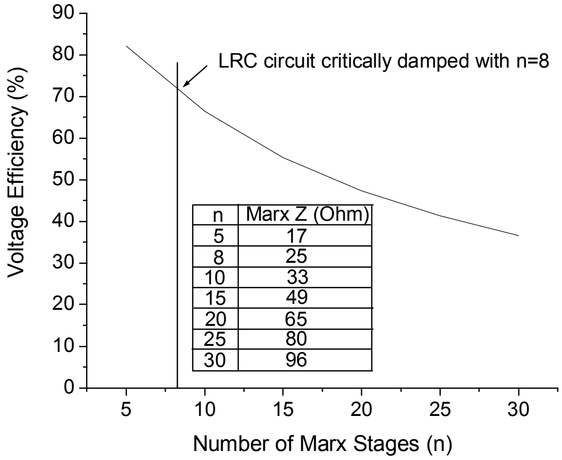


Figure 4. Marx LRC circuit approximation performance when equivalent stages are added.



n	Marx Z (Ohm)
5	17
8	25
10	33
15	49
20	65
25	80
30	96

Figure 5. Voltage efficiency of a Marx generator as equivalent stages are added, changing the circuit damping.

VI. WAVE ERECTION MARX

The transient wave erection Marx shown in Figure 6 differs from the Marx circuit of Figures 1 and 2 in its use of stray capacitance effects. The general Marx circuit does not force switches to close in succession. Therefore, switches can fire randomly, adding temporal jitter to the system's performance.

The transient wave Marx insures that after closure of the first switch, stray capacitances hold one side of each successive switch near ground until the switch fires. A voltage wave propagates toward the load with increasing intensity, triggering successive switches faster and faster until it reaches the load with sub-ns risetime and low jitter for output voltages of several hundred kV at moderate per pulse energies.

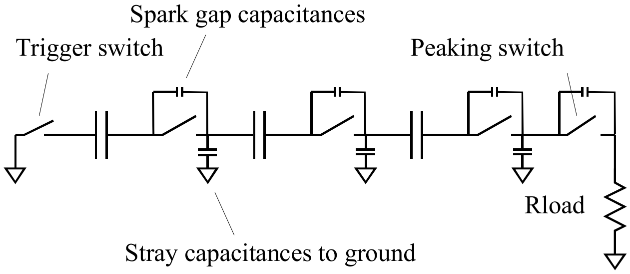


Figure 6. Transient wave erection Marx circuit.

The output waveform from a 17 stage transient wave Marx generator is shown in Figure 7. Notice the characteristic Marx output pulse shape, except for the front spike. The risetime is 250ps. A temporal jitter of 114ps RMS has been demonstrated by a 17 stage transient Marx, excluding the 15kV trigger generator circuitry.

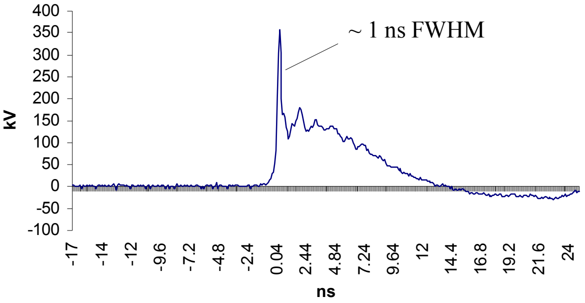


Figure 7. Transient wave Marx output waveform

V. CONCLUSION

Marx generators are effective systems for efficient voltage multiplication. For short pulse generation the Marx should operate near its critical damping due to a balance between voltage efficiency and overshoot. The transient wave erection Marx should be used where fast risetimes are critical.

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