SOLID STATE MARX MODULATORS FOR EMERGING APPLICATIONS*

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Abstract

Emerging linear accelerator applications increasingly push the boundaries of RF system performance and economics. The power modulator is an integral part of RF systems whose characteristics play a key role in the determining parameters such as efficiency, footprint, cost, stability, and availability. Particularly within the past decade, solid-state switch based modulators have become the standard in high-performance, high power modulators. One topology, the Marx modulator, has characteristics which make it particularly attractive for several emerging applications. This paper is an overview of the Marx topology, some recent developments, and a case study of how this architecture can be applied to a few proposed linear accelerators.

THE MARX TOPOLOGY

It is a futile task to completely capture all the implementations of Marx which have been developed. However, presented in this section is one way in which to describe a Marx and highlights several particular implementations which embody many of the strengths of the topology.

The Ideal Modulator

In the context of RF sources, the modulator is typically defined as the power converter interfacing the AC mains with the RF tube. In CW systems, it is common to refer to this interface simply as the power supply. Hence, the modulator is usually a pulsed supply.

The desired characteristics of a modulator are most effectively optimized in view of a specific implementation. However, some general positive attributes are common. First, the pulse quality of a modulator must be appropriate for the RF system. Output voltage, output current, pulse width, and pulse repetition frequency broadly classify the modulator. However, especially in linacs for light sources, secondary parameters such as timing jitter, pulsed amplitude stability, and flat-top droop are increasingly important.

The power input to the modulator is most commonly the AC mains. While it is possible to further sub-divide some modulators into a power supply and a pulse shaping unit, the view is typically most straightforward considering these to be one system. A consideration for the modulator is to draw a constant power with near-unity power factor from the mains. Some facilities are bound by regulatory requirements which dictate harmonic content at the point of common coupling with the utility, such as IEEE 519. An ideal modulator is lossless. Short of this, waste heat is most typically rejected to the facility water cooling system or the ambient atmosphere.

The availability, A, of a system is typically defined in terms of the mean time to repair (MTTR) and the mean time between failures (MTBR),

$$A = \frac{MTBF}{MTBF + MTTR} \qquad (1)$$

To enable very high availability numbers, redundant architectures can be used. This allows a component to fail without bringing down the system.

The cost of a modulator might be divided into three categories: the procurement costs, the maintenance costs, and the operation costs. The maintenance costs might include the manpower and replacement parts to repair and refurbish the system. Operation costs include utility needs and system configuration adjustments.

Secondary characteristics of interest include the ability of a modulator to operating into different impedance loads. During commissioning or operation of an accelerator at different configurations, the modulator may most efficiently interface with the RF source at a lower or higher output voltage. In the case, for example, of the klystron, this would necessitate modulator operation into a different effective impedance. The pulse shape characteristics must be appropriately preserved at these varying load conditions.

In addition, it is critical that the system is appropriately protected in the case of a load short. Both the modulator should remain undamaged and the modulator must prevent excess energy transfer to the load arc. This is one of the more challenging parameters for a modulator to produce.

General Marx Description

The Marx bank has been used as a high voltage generator since the patent from Erwin Marx in 1923. While there have been demonstrations utilizing inductive elements and opening switches, the most common embodiment uses capacitors and closing switches to construct the output pulse. Specifically: *A Marx modulator is a topology in which capacitors are charged in parallel during the recharge period and discharged in series during the output pulse.* A generic Marx circuit is shown in Fig. 1. In the case of modulators for linac applications, the pulse is repetitive, has a flat or shaped output, and can be terminated in the event of a detected fault. Therefore, turn-on and turn-off switching is necessary, and hence so is solid-state switching.

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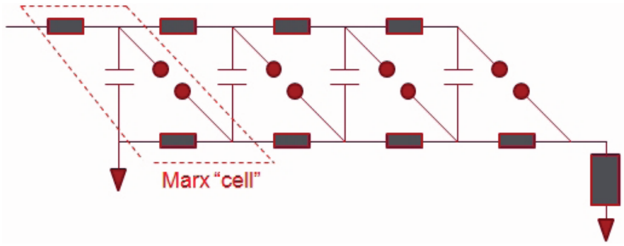

Fig. 1. Simple schematic of a capacitor-based Marx generator.

Turn-on Marx banks primarily using gas switches have been the work-horse of high voltage generators for many decades. At low powers, Marx-like topologies have been proposed with solid-state switching since the 1980's [1,2]. Only recently has the technology of solid state devices advanced to the point to enable solid modulators with peak powers capable of driving high-power vacuum tubes [3].

The simplest pulse characteristic that a Marx generator can produce is the RC-decay. The capacitance of the erected Marx discharges into a resistive load. The advantage of using the Marx topology rather than a single large capacitor and switch is that the maximum voltage across components in a Marx cell is the charge voltage. Therefore, relatively low voltage components can be used.

Further taking advantage of this characteristics, more complex circuits can be used in the Marx cell. For example, the output of the cell during a pulse might be a "chopped" waveform. In other words, a periodic square-wave can be generated during the pulse. Or, the cell itself can produce a square pulse. This can be enabled by placing a power electronics converter within the Marx cell. Finally, the cell can potentially produce an arbitrary shape on the output by using a pulse width modulated switching scheme in tandem with a low-pass filter.

In general, there are three characteristics of the Marx topology which are advantageous for emerging applications: modularity, low-voltage sub-units, and electrostatic adding. Recalling the ideal attributes of a modulator mentioned above, four attributes are desired: low cost, maintainability, availability, and pulse quality. A mapping of the Marx characteristics on the desired attributes of a modulator is given in table 1.

Table 1: Characteristics of the Marx topology compared with desired attributes for an ideal modulator.

	Modularity	**Low-Voltage Sub-Units**	**Electrostatic Adding**
Low Cost	All things being equal, many smaller units are more cost-effective to manufacture in bulk than fewer, larger units.	Components, in particular switches are commoditized and low-voltage. Synergy with other fields, such as the high-volume traction control market, can be used to develop modulators with off-the-shelf components.	Magnetics are not needed to support the whole pulse width. Therefore, large transformers are not necessary.
Maintainability	Several voltage or power levels of modulators within the same facility can utilize the same Marx sub-unit. This simplifies maintenance and lowers spares counts.	Pristine and carefully maintained surfaces are not critical at lower voltages. The most-maintained components are within the lower-voltage cells.	-
Availability	Redundancy can be built into the modulator. One or more modules can fail and not disable the RF station.	At lower voltage, precision diagnostics are more easily implemented. Therefore, for example, monitoring end of life indicators at the volt level is straightforward, while it would not be possible using a high-voltage diagnostic.	Each cell has a similar role in producing the output pulse; location within the array is not critical. Therefore, reconfiguration in the case of module failure is straightforward.
Pulse Quality	-	The macro pulse generated from the modulator is a combination of the individual modules. As such, fine details can be produced at the low-voltage level and preserved at the high voltage level.	Without using high-voltage magnetics, it is more-straightforward to produce a fast rise and fall-time pulse.

SELECTED IMPLEMENTATIONS

There are several recent embodiments of the Marx modulator topology which highlight some of the advantageous characteristics listed above. These are highlighted below.

Prompt turn-on

For the Electra krypton fluoride laser program, the Naval Research laboratory developed a solid-state short-pulse Marx modulator [4]. Using thyristors, the modulator produces the characteristics given in table 2. Magnetic assist is used in series with the switches to enable high di/dt (54 kA/µs) switching. The modulator has been operated for over 10 million shots and the switches have been separately tested for over 300 million shots without failure. This Marx represents a prompt turn-on scenario where all cells are triggered simultaneously. In addition, low-inductances techniques are used with magnetic switching to enable a very fast pulse.

Table 2. Characteristics of the NRL Marx modulator.

Voltage Output	-200 kV
Current Output	-5 kA
Repetition Rate	10 Hz
Pulse Width	~300 ns

Staggered turn-on

For the International Linear Collider (ILC) klystron modulator, several developments took place to provide an alternative to the previous baseline, the bouncer modulator. The characteristics of the modulator are shown in Table 3. Two particular modulators that were produced based upon the staggered turn-on mode of Marx modulator operation. The modulator from DTI [5] is shown in Fig. 2 while the SLAC P1 Marx [6] is shown in Fig. 3.

While these Marx banks have different implementations of the technology, they do a common characteristic with how they produce the flat output pulse. Because it is a long-pulse modulator, there must be an active correction scheme to ensure the output pulse remains flat. To achieve this, some cells do not turn on at the beginning of the pulse. They have delayed turn-on such that when the overall output droops to a certain level, the delayed cell turn-on raises the overall voltage to within the appropriate tolerance. The saw-tooth waveform on the top of the pulse remains within the +/-0.5% level.

Table 3. Characteristics of the ILC Marx Modulators.

Voltage Output	-120 kV
Current Output	140 A
Repetition Rate	10 Hz
Pulse Width	1.6 ms
Flat-top	+/- 0.5%

Figure 2. Photograph of the DTI ILC Marx Modulator.

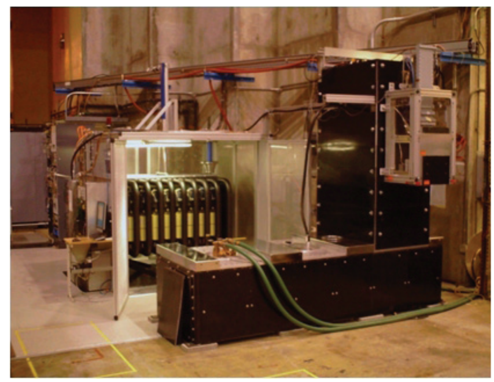

Figure 3. Photograph of the SLAC P1 Marx.

Filtered PWM output

For the European XFEL project, Thompson Scientific produced a "pulse step" Marx modulator [7]. The characteristics of this Marx are shown in Table 4. In this modulator, the cell output is a chopped pulse width modulated signal. By interleaving the outputs of the Marx cells, the ripple adds deconstructivly. A low pass filter on the output smooths the modulator output into a square pulse. This modulator pulses into output cables which feed a step-up transformer. The output is closed loop, enabling operation into many different impedance loads [8].

Table 4. Characteristics of the XFEL Modulator

Voltage Output	12kV
Current Output	2 kA
Repetition Rate	30 Hz
Pulse Width	1.7 ms

Flat-pulse output

The second-generation modulator developed at SLAC for the ILC application is the SLAC P2 Marx [9]. The characteristics of this Marx are given in Table 3. Among many structural and electrical evolutions from the P1 Marx, the P2 Marx uses a fundamentally different correction scheme. Each cell produces a square output

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pulse. A buck converter is placed in series with the main cell capacitance. This converter produces a "ramp-up" which exactly compensates the "ramp-down" of the main capacitor droop. The sum of the two signals is constant over the length of the pulse. A photograph of the finished modulator is shown in Figure 4.

Because large step-up transformers are not necessary, the rise-time of the Marx can be reduced compared to the baseline. For the P2 Marx, the rise and fall are <10µs. This is important such that wasteful energy is not deposited in the klystron collector prior to and after the RF pulse. In addition, as shown in Figure 5, a very flat output pulse is possible. Each cell has a deterministic ripple at a constant carrier frequency. Therefore, the cells can be interleaved, similar to the Thompson modulator, to cancel the ripple on the output of the modulator. Measured ripples of less than 0.05% have been demonstrated.

Figure 4. Photograph of the SLAC P2 Marx.

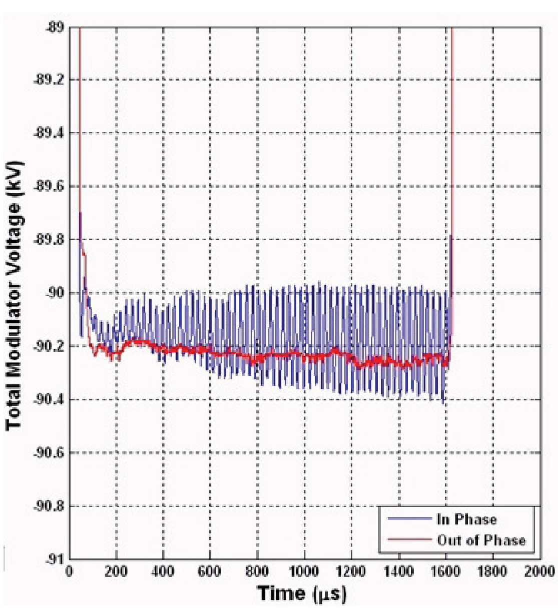

Figure 5. Measured output voltage for the SLAC P2 Marx. Shown is the output with the cells in phase and out of phase.

In addition, the SLAC P2 Marx uses the characteristic of the cells having relatively low voltage by having abundant diagnostic access. Each cell contains twelve, 12-bit, 1 MS/s ADCs to monitor parameters of interest within the cell.

EMERGING APPLICATIONS

One attribute of the Marx modulator is that it is a repeated structure of a modular cell. Fundamentally, the research and development can focus on this cell unit, such that it can be applied to many different applications. For example, several cells can be placed in series to produce a higher voltage. Alternatively, several can be placed in parallel to increase the output current. This is illustrated in Figure 6. The application of the SLAC P2 Marx cell for several emerging accelerator applications is presented in this section.

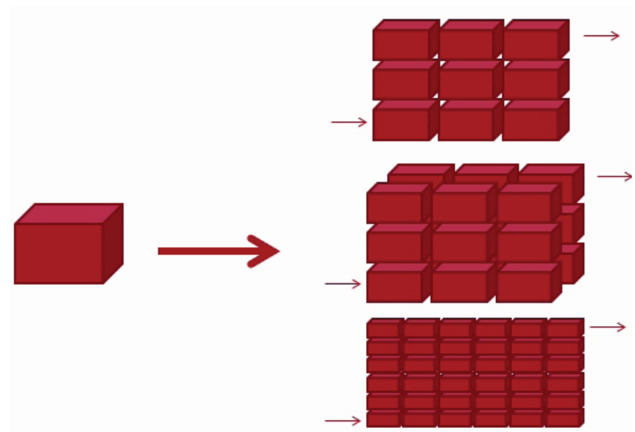

Figure 6. Scaling of a single Marx building block to several configurations.

ESS

The European Spallation Source is a next generation proton accelerator that is proposed to be implemented in Sweden [10]. While the characteristics of the RF system have not been finalized as of this publication, some preliminary values are given in Table 5. Using the same SLAC P2 Marx cell, a Marx modulator can be developed for the ESS application. While the average power requirements are higher, the cell dissipation is within the limits of the Marx cell. Assuming two different klystron operating voltages, two different Marx banks can be constructed. These are shown in Table 6.

Table 5. Preliminary characteristics of an ESS RF station.

Klystron Peak Power	4.8 MW
RF Pulse Width	14 Hz
Repetition Rate	3.4 ms

Table 6. Characteristics of an ESS Marx based upon the SLAC P2 Marx cell topology.

	# of cells	Max single cell loss	DC to pulse efficiency
SLAC P2 Marx	32	410 W	95%
80 kV ESS Marx	23	780 W	95.8%
113 kV ESS Marx	31	610 W	95.5%

CLIC

The Compact Linear Collider (CLIC) is a proposed high energy physics machine at CERN. [11] While the parameters of the drive beam klystron modulator are not finalized, some preliminary figures are shown in Table 7 [12]. The two particularly challenging parameters are the AC-pulse efficiency and the pulse amplitude reproducibility.

In the case of the pulse amplitude reproducibility, the characteristic of the P2 Marx of having precision diagnostics within the cell can be taken advantage of. If, for example, the modulator were to regulate on the output pulse of the modulator using a waveform digitized with a 12-bit ADC, the best possible resolution would be $1/2^{12}$, or 244 ppm. However, if the same 12-bit ADC we used on each of the n cells, the best possible resolution becomes $1/2^{12}/n^{0.5}$, or 38 ppm for a 40-cell Marx.

Table 7. Preliminary modulator characteristics for the CLIC drive beam klystron modulator.

Pulse Voltage	150 kV
Pulse Current	160 A
Pulse Width	140 µs
Reproducibility	10-50 ppm
AC-pulse Efficiency	90%
Pulse Repetition Frequency	5 Hz

Fermi 201 MHz Linac Upgrade

Fermi National Accelerator Laboratory desires to upgrade its 201MHz linac RF systems. One proposed method to improve the reliability of the system would be to replace the existing series-pass regulator based triode modulator with a Marx modulator. This application is particularly challenging because of the shaped output pulse. On a pulse to pulse basis, the output waveform of the modulator must change. For example, when the proton beam arrives in the cavity, the cavity voltage must be quickly increased to compensate for the loading. As such, the modulator output must rise. The timing of this is not consistent and also the magnitude must be dynamically changed.

This application is suited for the Marx modulator because of the ability of the modulator to both have staggered turn-on and off, and also because of the ability of the modules to produce ramping outputs. For example, if during the beam arrival time the voltage out of the modulator must increase gradually, the individual cells could produce a rising output. In a simple sense, the modulator can perform as an arbitrary waveform generator.

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