Inverse Marx modulators for self-biasing klystron depressed collectors

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A novel pulsed depressed collector biasing scheme is proposed. This topology feeds forward energy recovered during one RF pulse for use on the following RF pulse. The presented "inverse" Marx charges biasing capacitors in series, and discharges them in parallel. Simulations are shown along with experimental demonstration on a 62kW klystron.

Introduction: SLAC National Accelerator Laboratory (SLAC) is actively developing next-generation high-power RF sources. In response to a US Federal mandate [1] and growing particle accelerator demands, RF power source efficiency is gaining importance. One method for increasing efficiency, a depressed collector, is studied for application in pulsed RF systems.

In low duty cycle, high peak power (>1MW), short pulse (<1μs) RF systems, traditional depressed collector stage biasing methods can introduce cathode oscillations, affecting RF output phase and output. Decoupling the collector biasing from the driving modulator avoids these deleterious cathode oscillations and enables recovering the wasted energy in the rise and fall time; critical in short-pulse applications.

A self-biasing depressed collector was recently developed. In this method, collector stages dynamically float to potentials according to the impedance of the biasing network and the collected stage current. During the pulse, a step-down transformer builds up energy in a storage capacitor. This energy is then recovered back to the driving modulator in the inter-pulse time period [2]. This paper proposes an alternative biasing topology: the "inverse" Marx modulator. This is the first implementation known to the author of this variant of the Marx topology. The description of the circuit, PIC and circuit simulations, and experimental demonstration on a 62 kW pulsed klystron are in the following sections of this paper.

Circuit Description: Depressed collectors have been used for several decades as a means to recover energy from the spent beam of vacuum electron devices [3]. To efficiently collect the current, the stage potential should be just below the kinetic energy of the beam. Adding multiple stages at different potentials enables a broad spent-beam energy distribution to be efficiently recovered.

The Marx topology has been utilized in many applications and configurations for over 80 years [4]. A Marx bank (modulator) uses opening and closing elements (switches, transistors, diodes, etc.) to charge capacitors in parallel, and discharge them in series. Many low-voltage Marx stages can be arranged to form a single, high voltage pulse generator. An alternative arrangement magnetizes a series string of inductors, and then demagnetizes them in parallel.

In the "inverse" Marx, capacitors are charged in series, and discharged in parallel. A simple implementation is shown in Fig. 1. In a pulsed klystron depressed collector, the currents collected by the collector stages are effectively modeled as current sources. Here, two collector stages are represented by current sources driving two Marx stages. During the pulse, the switch, Q1, and diodes, D2 and D3, are open circuits and current flows through C1, C2, and D1. The current charges the capacitors, thereby increasing the collector stage potentials. Between pulses, Q1 closes, and the energy stored in C1 and C2 resonates through L1 and L2 back to the modulator for use on subsequent pulses. Note that diodes block excess energy from discharging into the collector in the event of an arc.

An example of the transient behavior of this circuit is shown in Fig. 2. A two-stage collector drives a 16-stage inverse Marx. As shown, the stage potentials rise approximately linearly over the duration of the pulse. The rise and fall times of the pulse also transfer energy to the Marx capacitors. This is illustrated by additional rise of the stage potentials after about 3.8μs, the end of the beam flattop.

The inverse Marx is a pulsed, step-down modulator. It features many potential "tap-offs" (an analog to a multi-tap, step-down transformer) on the high voltage side of the converter. The voltage at the output of this converter is ideally near the working voltage of the klystron modulator.

There are several advantages of this approach. First, the number of collector stages is smaller than the number of Marx stages. Cost-efficient, low-voltage components make up the Marx stages and bias the collector stages to a high voltage. Second, there is no fundamental limit to the pulse length. However, in practice, the collector stage potentials will rise to values where they no longer efficiently recover energy. Third, while the implementation shown in Fig. 1 shows an active switch, for short-enough pulses, inductors can be used to isolate the stages. In addition, even a semiconductor switch can be biased in such a way to not require an external trigger. This results in an entirely passive energy recovery scheme. Fourth, only some of the elements (ex. C1, C2, and D1 of Fig. 1) must be rated for the full pulse current. The remaining elements are rated for the lower, inter-pulse recovery current.

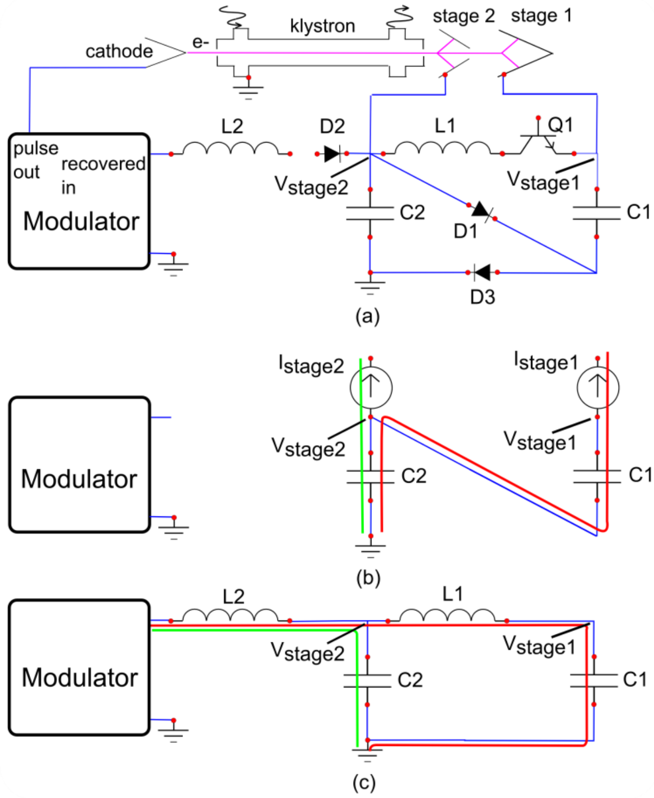

Fig. 1 *(a) Circuit schematic of a two-stage inverse Marx. Equivalent circuit (b) during the pulse and (c) during the inter-pulse period. Current paths are highlighted by red and green traces.*

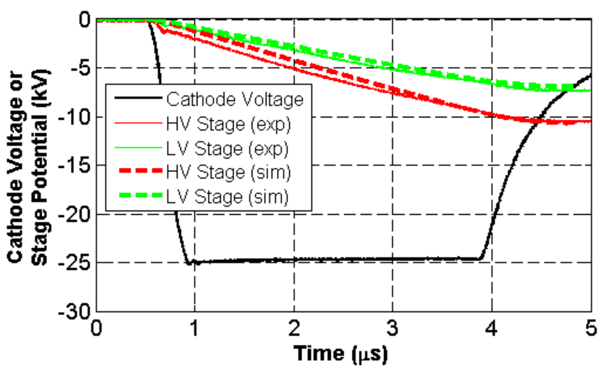

Fig. 2 *Measured (solid lines) and simulated (dashed lines) stage voltages and cathode voltage for the SLAC subbooster klystron. The inverse Marx has sixteen stages. The high voltage collector stage attaches to the sixteenth Marx stage and the low voltage collector stage attaches to the ninth Marx stage.*

To demonstrate this topology, a SLAC "subbooster" S-band klystron was modified with a two-stage depressed collector [2]. This permanent-

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magnet focused klystron has a beam voltage of 25kV, beam current of 8.8A, output RF power of 62kW, and, for this study, a pulse width of 3.1 µs.

Utilizing PIC codes, the klystron is modeled from the cathode to collector [5]. In the PIC model, the net current into each stage was simulated for various DC biasing conditions. In increments of 1kV, both the low and high voltage collector stages were modeled from 0kV up to -19kV. In other words, 20x20=400 separate simulations were run. Resulting is a table containing stage currents for each DC biasing condition.

A sixteen-stage inverse Marx is designed. For simplicity, the recovered energy dissipates in a resistive load instead of resonating back to the driving modulator. The switch, Q1, and inductor, L1, of Fig. 1a is replaced by a large resistor. This resistor is effectively an open circuit during the pulse, and a load in-between pulses.

For the transient simulation, a PSPICE circuit models the inverse Marx. Pulsed currents with temporal profiles equal to the experimental pulsed currents are used as sources for the circuit model. For the first iteration, zero stage biasing is assumed. The currents into each stage are determined by the lookup table derived above. The circuit simulation results in a time-varying voltage for each collector stage. Next, the stage currents corresponding to this time-varying stage bias are then calculated according to the lookup table. These currents are then used as sources for the next circuit simulation. This process repeats until convergence.

Results are shown in Figs. 2 and 3. In Fig. 2, measured and simulated stage potentials are compared during the pulse. The post-pulse behavior is illustrated in Fig. 3. The exponential decay is due to the load resistance discharging/charging the diode capacitances. Without these stray capacitances, the stage potentials instead quickly drop to the Marx capacitor voltage.

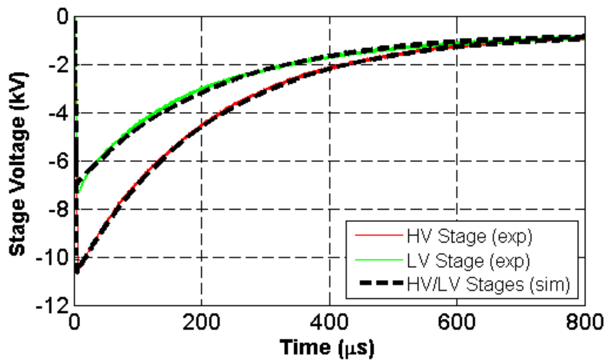

Fig. 3. *Zoomed-out view of data shown in Fig. 2.*

The temporal characteristics of the inverse Marx as presented above have an avoidable inefficiency. At the beginning of the pulse, before the capacitors charge up, there is nearly zero potential depression. Therefore, there is minimal energy recovery. It is instead desirable for the potentials to quickly rise to the optimal level for the duration of the pulse. To overcome this, a "pre-charge" can exist on the biasing capacitors prior to the pulse. This is the natural condition if a CLC circuit resonates energy back to a modulator.

Alternatively, transmission lines can be used for transient isolation of the biasing capacitors during the pulse. In the previous example, approximately -10kV is desired on the high voltage stage for a, say, -4A stage current. This requires a transmission line with a characteristic impedance of 2.5 kΩ, which is challenging to physically realize. Stacking transmission lines as shown in Fig. 4 allows lower-impedance transmission lines to be used. If the two-way transit time of the transmission line is longer than the applied current pulse, the effective impedance seen by the collector stage is the individual line impedance times the number of Marx stages.

To illustrate the concept, this arrangement is simulated with current sources. Results are shown in Fig. 5. Here, trapezoidal stage currents translate into trapezoidal stage potentials. For the simulation, transmission lines with a one way transit time of 2.2 µs were used. Again, sixteen Marx stages were used with tap-offs at the sixteenth and ninth stages. The absolute voltage of each stage biasing capacitor is also shown. After the transit time of the transmission line, the voltage rises on each capacitor. At about 8.5µs and 12.5µs, the effect of reflections is seen on the stage potentials. To eliminate reverse reflections on the stages, an "end of the line clipper" diode is used. Note that for relatively long pulses (>1µs), it becomes impractical to use physical transmission lines to provide transient isolation. One might instead utilize an LC lumped-element approximation such as a pulse forming network.

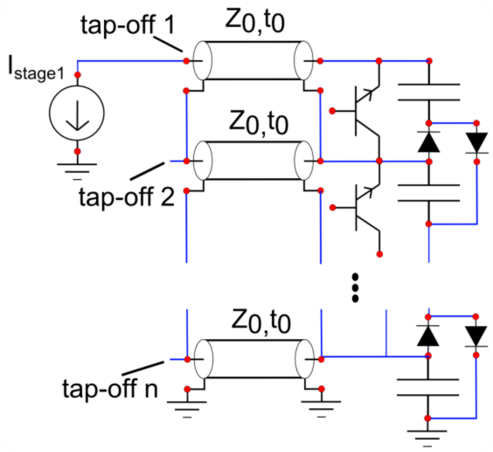

Fig. 4 *Schematic of an inverse Marx with transient isolation between the collector stages and the biasing capacitors.*

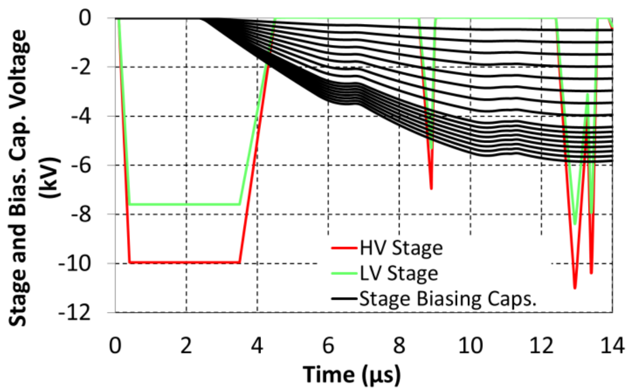

Fig. 5. *Circuit simulation of the biasing arrangement shown in Fig. 4.*

Conclusion: The concept of an inverse Marx has been presented, simulated, and experimentally demonstrated on a pulsed klystron depressed collector. Next steps include demonstrating the square pulse variant. SLAC is undergoing studies on the applicability of this technology for multi-megawatt, short and long pulse klystrons.

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