Solid State Marx Generator

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Abstract

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Marx generators can produce high voltage pulses using multiple, identical stages that operate at a fraction of the total output voltage without the need for a step-up transformer that limits the pulse risetimes and lowers the efficiency of the system. Each Marx stage includes a capacitor or pulse forming network and a high voltage switch. Typically these switches are spark gaps resulting in Marx generators with low repetition rates and limited lifetimes. The development of economical, compact, high voltage, high di/dt, and fast turn-on solid state switches makes it easy to build economical, long lifetime, high voltage Marx generators capable of high pulse repetition rates.

We have constructed a Marx generator using our 24 kV thyristor based switches, which are capable of conducting 14 kA peak currents with ringing discharges at > 25 kA/µs rate of current risetimes. The switches have short turn-on delays, less than 200 ns, low timing jitters and are triggered by a single 10 V isolated trigger pulse.

This paper will include a description of a 4-stage solid state Marx and triggering system as well as show data from operation at 15 kV charging voltage. The Marx was used to drive a one-stage argon ion accelerator.

INTRODUCTION

Applied Pulsed Power, Inc. (APP) has developed compact solid state switches [1] to replace spark gaps in a variety of applications. Four of these switches were used to build an air-insulated, solid state Marx generator for the purpose of accelerating argon ions as part of a Department of Energy-funded ion source development program [2]. A Marx generator uses multiple stages that are effectively charged in parallel and discharged in series to produce a high voltage pulse. The high voltage pulse is only present for a brief period, which greatly relieves the constraints on the overall system insulation. No step-up transformer is required, enabling fast voltage risetimes to be obtained. This greatly improved the resolution of time of flight measurements performed on the ion source. The solid state switches are easy to use and trigger. The complete solid state Marx generator was assembled and used to conduct acceleration experiments in the same day.

SOLID STATE SWITCH

The switches used in the Marx generator were developed to replace spark gap switches in a variety of applications. These switches will be discussed briefly here, and are described in more detail in another paper at this conference. The switches are capable of operating at currents up to 10 kA for high repetition rates, di/dt's of 30 kA/µs, and can handle large reverse currents. Fig. 1 is a picture of one switch. Fig. 2 shows a comparison of current waveforms for the switch and a spark gap used in a commercial application. The switches incorporate small GTO-type silicone thyristors using a patented packaging and triggering scheme [3,4]. Only one stage of the switch is command triggered; the remaining "auto-triggered" stages are simultaneously triggered as the voltage on the first stage begins to fall. The gate drives are powered by the voltage across the switch, eliminating the need for an external gate power supply. Triggering is accomplished with a 15 volt, fast rising, few microsecond wide pulse. The thyristors are capable of fast turn-on.

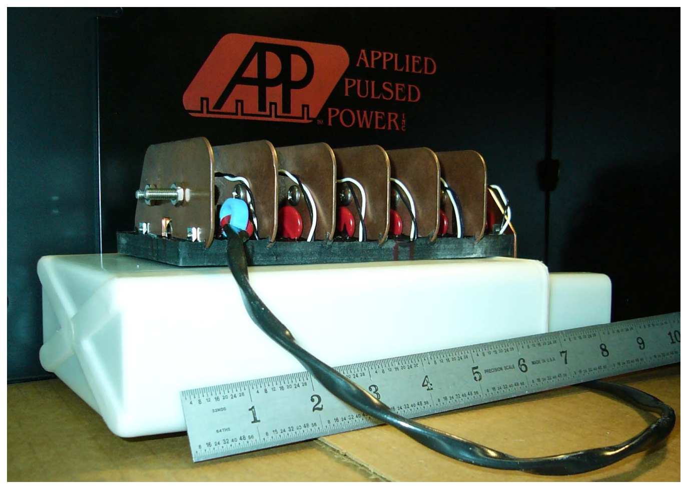

Fig 1. Solid state switch attached to a 0.15µF Capacitor

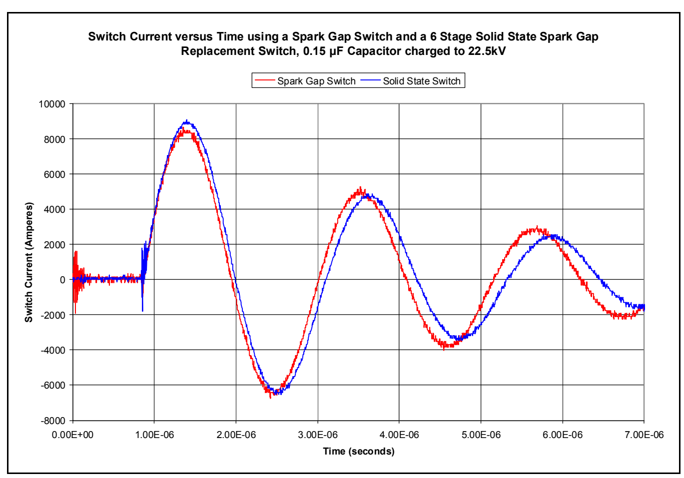

Fig 2. Comparison of Switch Currents for the Solid State and a Spark Gap Switch

Fig. 3 shows the load voltage waveform for a switch with a single thyristor switching a 33 Ω PFN, made from 33 Ω coaxial cable, charged to 4 kV, into a 33 Ω load, resulting in a pulse with a 10%-90% rise time of < 100 ns.

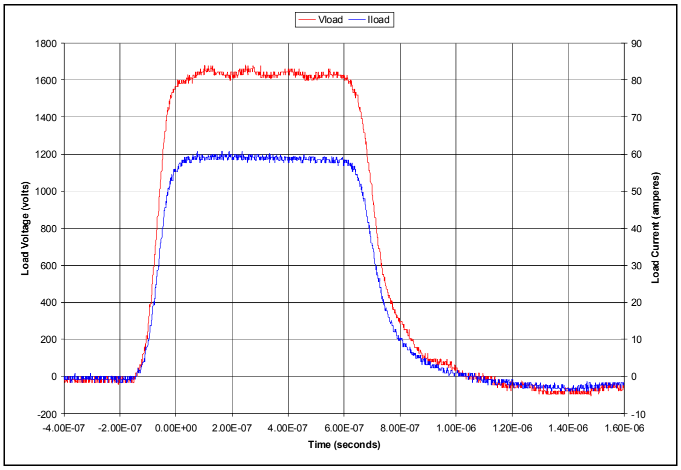

Fig. 3. Load Voltage versus Time, 33 Ω PFN, Charged to 4 kV, into a 33 Ω Load.

SOLID STATE MARX GENERATOR

The Marx generator uses 4 stages operating at up to 20 kV, which are effectively charged in parallel and discharged in series to produce up to an 80 kV pulse.

A simplified schematic of the modulator is shown in Fig. 4. The 20 kV power supply, charges C1 through C4 via common mode chokes, L1 – L4. S1 – S4 are the 24 kV solid state switches. The primaries of trigger transformers T1-T4 are connected in series to insure simultaneous triggering. As a result an 80 V trigger pulse is required. The primary winding is a single turn of Belden type 8866 high voltage cable looped through the 16mm diameter ferrite core on the command triggered stage of each switch. A single cable runs through all 4 transformers. The trigger generator sits at ground potential but the cable insulation can withstand >100kV, eliminating the need to run the trigger through the common mode chokes. It is also unnecessary to connect a reverse biased high voltage diode across each stage as is sometimes done to protect solid state switches from overvoltage, should one switch prefire or fail to trigger. As these diodes must be rated for the full stage voltage and Marx output current, they represent the addition of a substantial amount of silicon. Should a misfire occur in our Marx, the auto trigger circuits on each switch sense the start of the current flowing through the snubber capacitors and simultaneously trigger all of the switches before they are over-voltaged. The Marx operates in air.

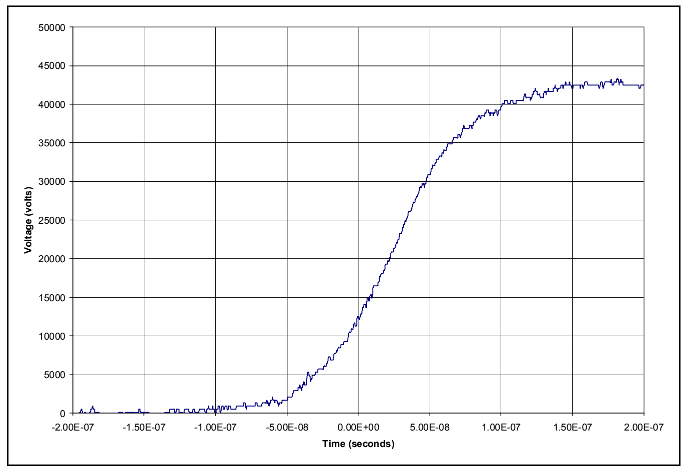

Fig. 5. Marx output voltage for a 12 kV charging voltage

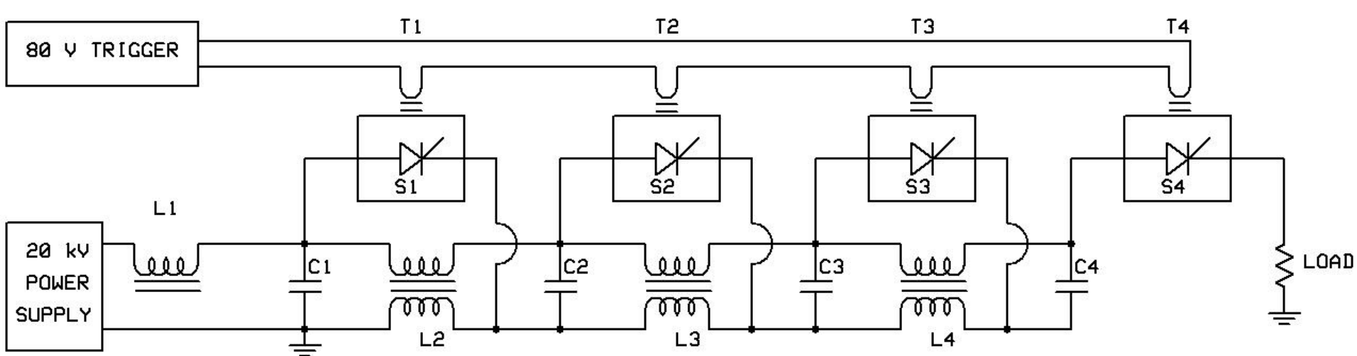

Fig. 4. Simplified schematic of the solid state Marx generator

TIME OF FLIGHT ANALYSIS OF THE ACCELERATED ARGON ION BEAM

The solid state Marx was developed to accelerate argon ions as part of a Department of Energy-funded ion source development program. A section view of the acceleration experiment apparatus is shown in Fig. 6. The ion source and modulator, including a 30cm plasma drift region, were installed in a stainless steel cylinder located inside the vacuum chamber. This cylinder was held in place by a high voltage insulator, allowing the cylinder to be pulse charged to up to 100 kV with respect to the grounded vacuum chamber. This insulator also serves as the vacuum/air interface. The ion source and modulator pulsed power supplies were connected to a 500VA UPS, all of which were located inside of a copper faraday cage. This enclosure was electrically connected to the ion source and anode assembly in the vacuum chamber. A high voltage insulator was used to insulate the enclosure from the vacuum chamber. This enclosure was isolated from ground during the acceleration using a high voltage air operated relay on the 110VAC line. Triggering and diagnostic functions were carried out via fiber optic cables.

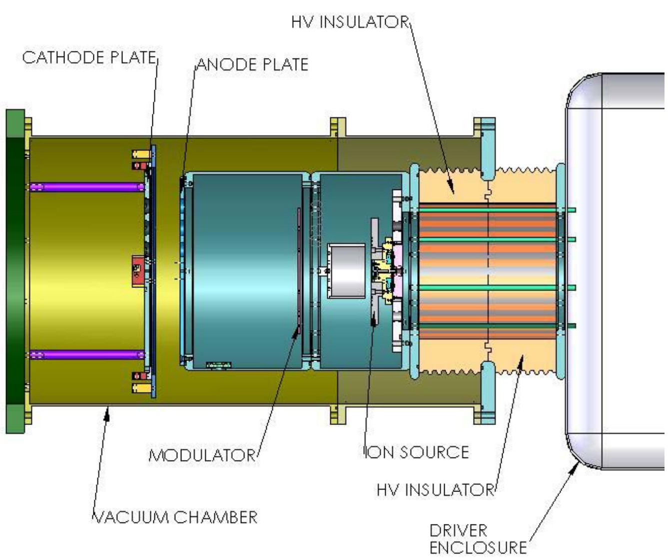

Fig. 6: Section view of apparatus for ion acceleration experiments. Anode and cathode electrodes are not shown.

The cathode plate was electrically connected to the grounded vacuum chamber, allowing the diagnostics used for the accelerated beam to operate at ground potential. Not shown in Fig. 6 are the anode and cathode electrodes which could be attached at several radial and azimuthal locations on the anode and cathode plates

At first, a thyratron switched capacitor bank and an air core step-up pulse transformer produced the acceleration voltage. The voltage risetime for this system made the time of flight analysis of the accelerated ion beam difficult. This was replaced by the solid state Marx. Fig. 7 shows a comparison of the acceleration voltages produced by the two systems. The effective capacitance of the Marx was less than the transformer based system, which results in faster decay of the acceleration voltage, but is not important for this application.

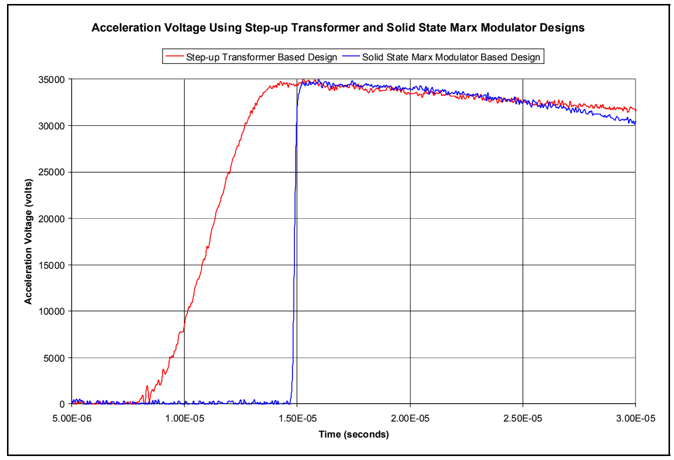

Fig. 7. Comparison of Acceleration Voltage using Step-Up Transformer and Solid State Marx Generator

Analysis of the accelerated ion beam for time of flight was used to examine the species existing in the ion beam. Fig. 8 shows a typical data sets.

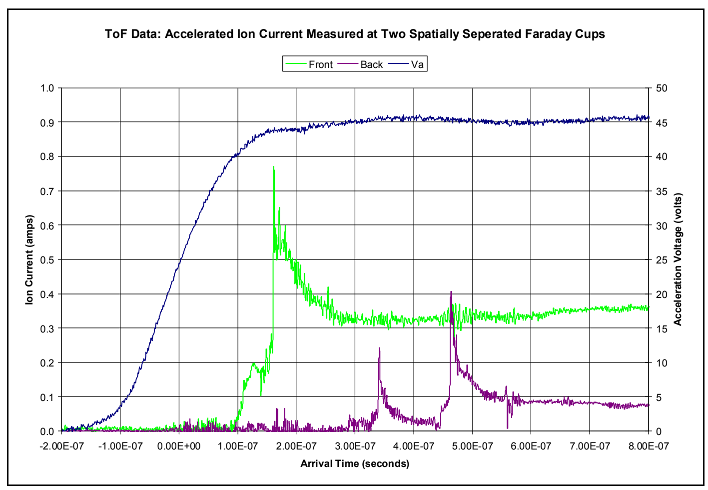

Fig. 8. Faraday Cup Current at Two z locations

The acceleration voltage waveform was used to predict the arrival times for Ar^{1+} and Ar^{2+} as seen in Fig. 9. Comparing these figures clearly demonstrates that Ar^{1+} and Ar^{2+} both exist in the accelerated ion beam at a ratio of about 8:1. This does not correlate with the spectrographic data as previously reported. While that data did clearly show the existence of H, C, N, and O in the plasma, there was no trace of Ar^{2+} above the noise level of the detector. Given the evidence that the Ar^{2+} ion current is not derived from Ar^{2+} from the source, the logical conclusion is that it is created in the acceleration gap.

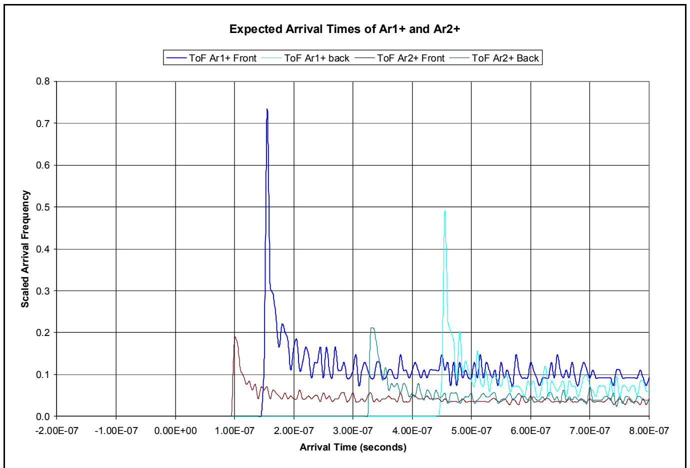

Fig. 9. Calculated Arrival Times Given Known Acceleration Profile for Ar^{1+} and Ar^{2+}

The acceleration voltage waveform was then used to analyze for H, C, N, and O. The H peak at the forward faraday cup was at -0.03 µs and at 0.055 µs at the rear FC. For C, the times were 0.07 µs and 0.26 µs. For N the times were 0.08 µs and 0.29 µs. Finally, for O the arrival times were 0.09 µs and 0.305 µs. The time of flight data does show small peaks around these times, indicating that these elements existed in the accelerated ion beam at ratios less than 1:50 to the Ar^{1+} ion current.

SUMMARY

Solid state Marx generators can have advantages for many applications. Also, by replacing the capacitors with pulse forming networks (PFN), this approach can be used in applications currently served by line type modulators. Some of the advantages of the thyristor switched capacitor or PFN Marx modulator include:

1) The solid state switches are compact, easy to use and simple to trigger while providing reliable, long lifetime operation.
2) The step-up pulse transformer is eliminated, resulting in faster pulse risetimes and higher efficiency.
3) Very high voltages are present only during the pulse, lowering insulation, and power supply requirements.
4) The modulator is comprised of multiple, identical, lower voltage modules that can be built and tested easily and be mass produced in volume and at low cost.
5) Only the energy for a single pulse is stored in the Marx, minimizing energy available to cause damage resulting from modulator or load faults.
6) The PFN's can be designed to obtain a variety of different pulse shapes.
7) High efficiency is achieved as a result of fast risetimes and low parasitic capacitance.
8) The overall system is compact and inexpensive in comparison with other Marx modulators and more conventional modulator designs.

REFERENCES

[1] S. C. Glidden and H. D. Sanders, "Solid State Spark Gap Replacement Switches", Proceedings of the 15th IEEE Pulsed Power Conference, Monterey CA, June 2005.

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[3] S. Glidden, "Compact High Voltage Solid State Switch", United States Patent number 6,624,684 B2 (2003).

[4] S. C. Glidden and H. D. Sanders, "Multi-Stage High Voltage Solid State Switch", United States Patent Application number 10/905,982.