

LONG LIFETIME OPTICALLY TRIGGERED SOLID STATE MARX

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Abstract - Marx generators are used to produce high voltage, high current, short pulses for a variety of applications. High energy Marx generators are typically switched by gas insulated spark gaps, which have short lifetimes, $<10^5$ pulses, thus limiting practical applications of the Marx generators. APP has developed optically triggered, economical, compact, 48kV, $>30\text{kA}/\mu\text{s}$, 8kA, and 100ns turn-on solid state switches and examined their performance under normal and fault-mode operating conditions in Marx generators. With 48kV Compact Solid State switches, $>10^7$ pulse lifetime, high voltage Marx generators capable of high pulse repetition rates can be built.

Three different Marx configurations have been tested; a conventional unipolar Marx, a unipolar Marx that uses magnetic assist to achieve $>70\text{kA}/\mu\text{s}$ current risetimes, and an inverting LC mode.

For practical applications, solid state switches must survive system faults, such as shorts in downstream components or the load, which can result in twice the normal forward current, a large reverse current and with a large fraction of the system energy deposited in the switches. The switches should also tolerate trigger failures that can result in overvoltage of one or more switches.

This paper will include a description of the solid state Marx and triggering system and show data from multi-million pulse operation as well as fault mode survival testing such as load shorts and switch triggering failures.

Near-term applications for the switches include the retro-fitting of the 5pps Marxes used for the Electra laser pre-amplifier and main amplifier. Electra is a repetitively pulsed, electron beam pumped Krypton Fluoride (KrF) laser at the Naval Research Laboratory. This program is developing technologies to meet the Inertial Fusion Energy (IFE) requirements for durability, efficiency, and cost. The technologies developed on Electra should be directly scalable to a full size fusion power plant beam line. The present Electra Marxes use gas insulated spark gap switches with lifetimes of 10^5 pulses. By using the 48kV Compact Solid State switch, lifetimes in excess of 10^7 pulses are expected.

I. INTRODUCTION

We have designed and manufactured 48kV Compact Solid State switches for use in Marx configurations based on APP's existing solid state switch technology. The quality control and lifetime testing that have been completed demonstrate that

these switches can have $>10^7$ pulse lifetimes. Using these switches, various different Marx configurations have been designed, built and tested.

II. 48kV COMPACT SOLID STATE SWITCH

The model S33A-12 48kV Compact Solid State Switch is comprised of a set of 12 model S38 modules in series. [1],[2] The S38 contains a single thyristor capable of 5 kV 14 kA, 50 kA/us operation. The S38 can tolerate high reverse current. All stages of the S33A are configured so that current through their snubber networks drives the gates of the S38 modules. Two of the stages are also configured to be triggered by an optical source that causes these modules to begin to turn-on. This initiates a change in voltage across the other stages, generating snubber current through the whole switch, thereby causing the whole switch to turn on. Fig. 1. is a picture of the S33A-12.

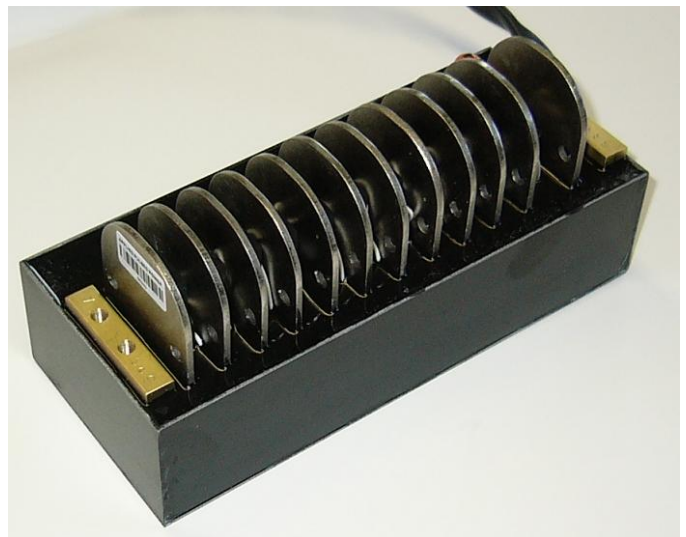


Fig. 1. Example Stage Circuit

This technique can be used because the snubber current during turn-on is 5 or 6 orders of magnitude greater than during the charging of the Marx. The advantage of this configuration is that the switch will not be damaged by un-triggered events. The optically triggered gate drives are self powered using energy in the snubber circuit so no external

power supply is required. The energy stored in the snubber circuits is dissipated in the switch. This energy is typically <0.5% of the switched energy.

III. QUALITY CONTROL

Each 48kV switch has 12 model S38 modules. These modules are each tested at high current, high di/dt and full voltage to assure proper operation. A set of these modules have been lifetime tested at the same parameters without failure. Fig. 2 shows the quality control test station and Fig. 4 shows the test current and voltage waveforms.



Fig. 2. Quality Control Test Station

The test configuration was 500nF charged to 4kV and a 0.2Ω load. The circuit inductance was about 100nH. This results in about a 70% switch efficiency. The turn-on time was about 180ns using an electronic trigger source rather than the optical trigger source.

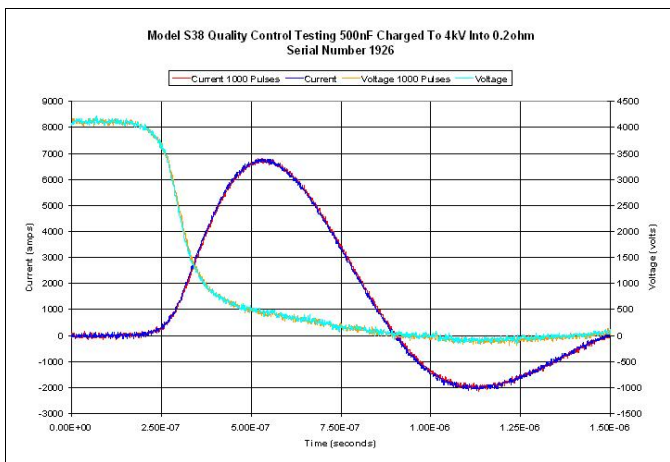


Fig. 3. Quality Control Test Current and Voltage Waveforms

Fig. 4. shows the Lifetime Test Station. It has 10 stations running at 20Hz continuous operation at full voltage and high current. The current and voltage waveforms are the same as in Fig. 3. We have tested over two dozen modules, some to more than 10^8 pulses without any module failing.

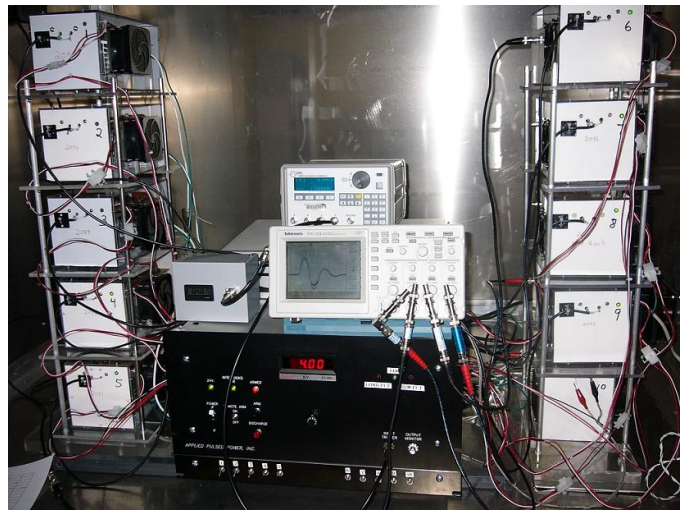


Fig. 4. Lifetime Test Station

A mean module lifetime greater than 10^8 pulses implies that a Marx with 100 48kV Compact Solid State Switches would have a mean time before failure of at least 10^7 pulses.

IV. SOLID STATE MARX CONFIGURATIONS

Three different solid state Marx configurations have been tested and a fourth has been designed and is being built. The three configurations that have been tested are a conventional unipolar Marx, unipolar Marx with magnetic assist, and an Inverting LC Marx. A distributed pulse compression Marx has been designed.

A. Conventional Unipolar Marx

A four stage conventional unipolar Marx was built with an 80nF capacitor and a 48kV S33A solid state switch per stage. It was not necessary to connect a 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 trigger fault occur in the 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. Fig. 5. shows Marx current data from this system when all switches are triggered compared to the current when the trigger fiber optic cable is removed from one switch. The only change in the output is a 15 ns delay. Fig. 6. shows the voltage on the untriggered switch.

Fig. 7. shows the a portion of rising Marx output current from 5 random pulses while operating at 2pps. The sensitivity of the oscilloscope was increased to improve resolution. The Marx jitter is within the 1ns resolution of this measurement. This Marx achieved switching efficiencies greater than 90%.

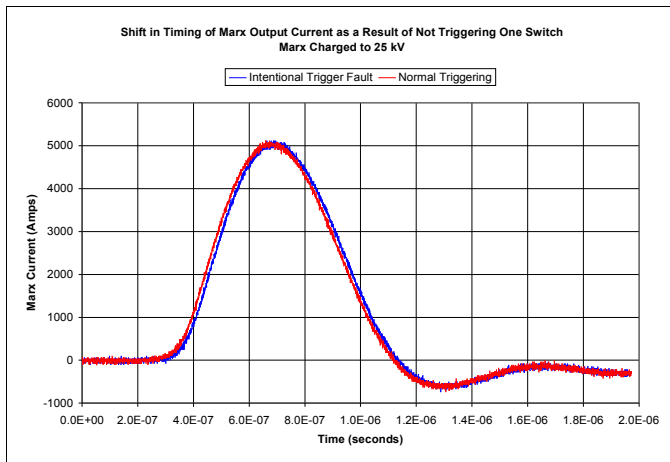


Fig. 5. Conventional Unipolar Marx Test Results Showing Effect of Trigger Fault on One of Three Switches

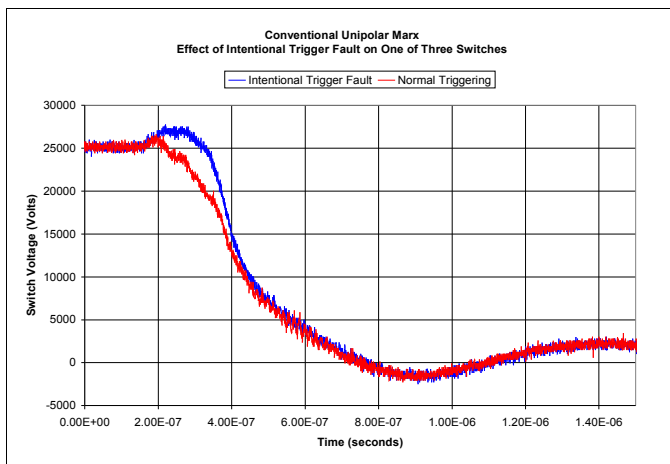


Fig. 6. Voltage on Switch with Intentional Trigger Fault

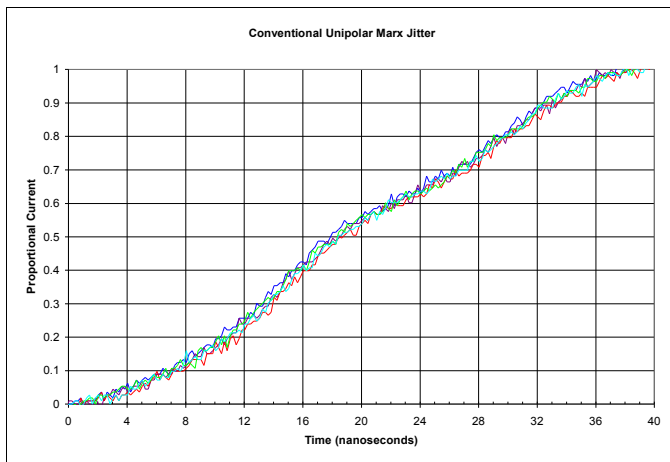


Fig. 7. Marx Jitter

B. Unipolar Marx with Magnetic Assist

PLEX Inc. designed, built and tested a twelve stage Unipolar Marx with magnetic assist. Saturable inductors on

each switch provide a short delay that allows the switch more turn-on time prior to high di/dt. This system has achieved $>70\text{kA}/\mu\text{s}$ and $>90\%$ efficiency. This design has been tested to $>10^6$ pulses at 7.5kA peak current and 300ns FWHM. Fig. 8 shows a picture of the Marx provided by PLEX, Inc.



Fig. 8. Picture of the Unipolar Marx with Magnetic Assist

C. Inverting LC Marx

A two stage inverting LC Marx was built using two 80nF capacitors and a 48kV Solid State Switch per stage. An example inverting LC Marx circuit is shown in Fig. 9. Fig. 10 shows data from this system. The peak load voltage is less than 4 times the charging voltage because a resistor in parallel with the load capacitor is used to dissipate some of the energy to prevent 100% current reversal. This Marx also achieved switching efficiencies greater than 90%.

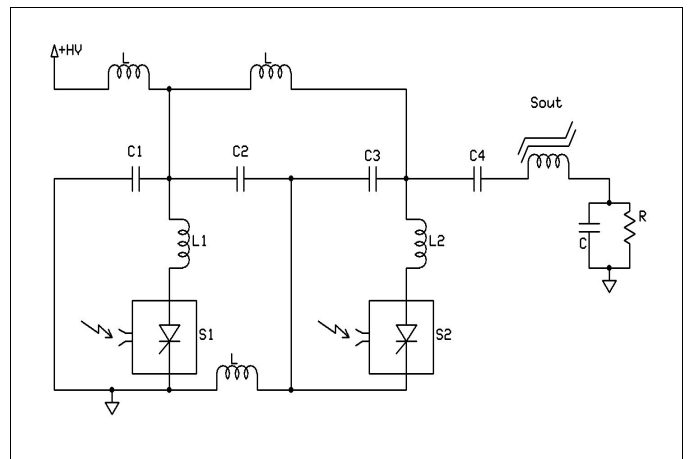


Fig. 9. Example Inverting LC Marx Circuit Model

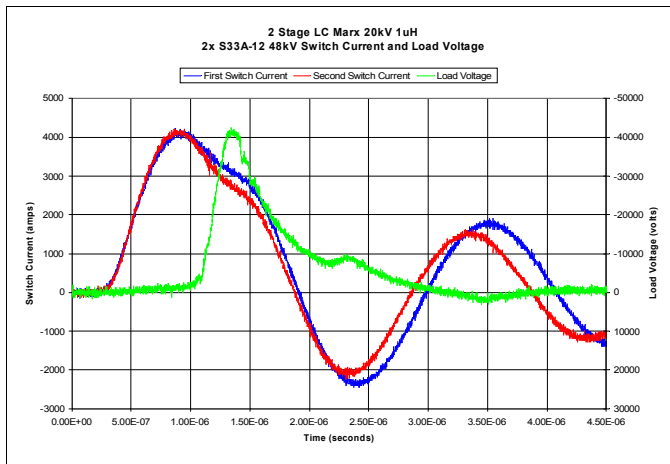


Fig. 10. Inverting LC Marx Test Results

Fig. 11. compares data from 2 pulses, with the trigger cable to one switch disconnected on one pulse. Unlike the conventional Marx topology, the switches are isolated resulting in a long delay before the un-triggered switch self triggers. This results in a substantial reverse current with additional energy deposited in the switch which must be taken into account in determining the maximum normal operating current for the switches. This can be addressed by adding a second trigger cable between adjacent switches. The trigger cable would be isolated from each switch at 48kV.

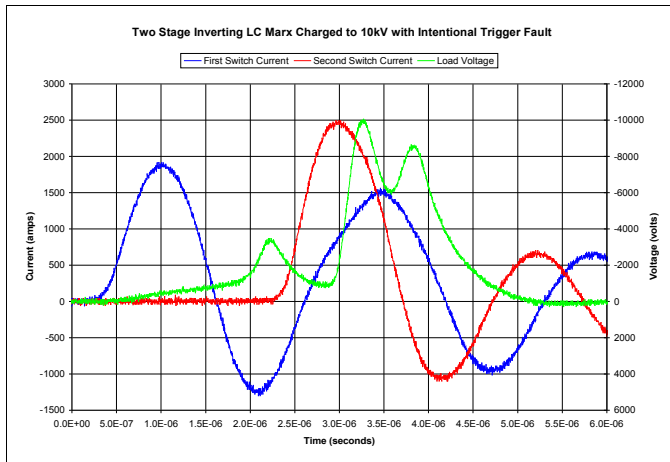


Fig. 11. Inverting LC Marx Test Results Showing Effect of Trigger Fault on One of Two Switches

D. Distributed Pulse Compression Marx

One way to reduce the number of switches required is to add pulse compression to the Marx. Additional pulse

compression can be added downstream of the Marx requiring high voltage and high power pulse compression components. One way to reduce this is to distribute the pulse compression throughout the Marx using lower voltage and lower energy components. By using a gain of 3, the number of switches can be reduced by a factor of 3. Based on this concept, we have designed a Marx with distributed pulse compression. An example of this design can be seen in Fig. 12. A test Marx using this configuration is under construction.

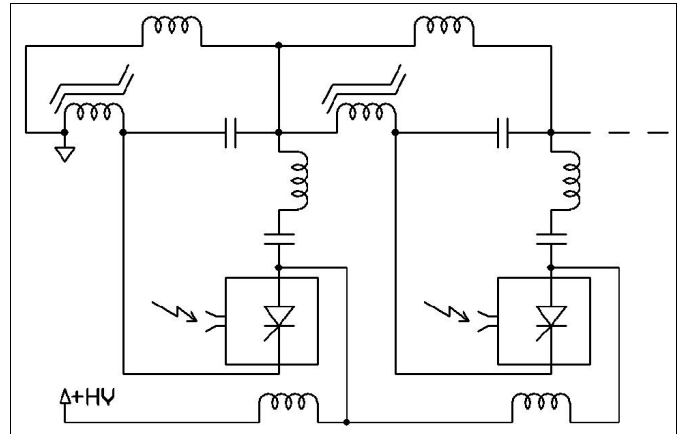


Fig. 12. Example Distributed Compression Marx

VII. CONCLUSION

Using the 48kV Compact Solid State Switches, greater than 10 million pulse lifetime, high voltage Marx generators capable of high pulse repetition rates can be built. Applications for the switches include the retro-fitting of the 5pps Marx used for the Electra laser amplifier at the Naval Research Laboratory, Laser Plasma Branch. [3]

REFERENCES

- [1] S. C. Glidden and H. D. Sanders, "Solid State Spark Gap Replacement Switches", 2005 IEEE Pulsed Power Conference, Monterey, CA, June 2005
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- [3] J.D. Sethian, et. al., "The Electra KrF Laser Program" 2001 IEEE Pulsed Power Conference, Las Vegas, NV, June 2001. IEEE, New York, NY p 232 (2002)