PULSED MODULATOR FOR AN IEC NEUTRON SOURCE*

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Abstract

This paper discusses the design and construction of a 1/10th scaled prototype pulse modulator for an IEC neutron source. The scaled prototype modulator has an output voltage of 13 kV and an output current of 10A. A significant feature of the modulator is that it has a variable pulse width (50 μs – 1ms) with < 5% droop at all pulse widths. The modulator operates with a duty factor up to 5% and has a maximum pulse repetition frequency of 1 kHz. Preliminary test results are given.

I. INTRODUCTION

A pulse modulator for an Inertial Electrostatic Confinement (IEC) neutron source is currently under development at Los Alamos National Laboratory (LANL). The design and operation of an IEC neutron source is discussed in more detail in the references [1]. In general terms, an IEC neutron source requires a high electric potential be maintained between two grids within a hydrogen plasma. These grids are most often arranged as concentric spheres. The grid potential accelerates the hydrogen ions and creates stable ion orbits. When isotopes of hydrogen, such as deuterium or a mix of deuterium and tritium, are used to form the plasma, neutrons are produced from the nuclear fusion resulting from the energetic collision of these nuclei.

The grid potential, often in the range of 100 – 200 kV, is generally established with DC power supplies. Current-limiting resistors are used between the power supply and the grid to protect the power supply from overcurrent resulting from an arc within the plasma. While effective at protecting the power supply this current-limiting resistor dissipates a significant amount of power.

The use of a pulsed modulator to supply the grid potential will have several benefits. One is the ability to produce a pulsed source of neutrons from an IEC device. This is important because there are several applications which require a pulsed source of neutrons. The pulsed modulator is also designed to run at a high duty factor, up to 5%. When the modulator is run in this mode the pulsed neutron source looks much like a continuous source of neutrons. Therefore, only one power supply is necessary for both pulsed and continuous modes of operation.

Another benefit of using a pulsed modulator is that it has the potential to improve system efficiency. The current-limiting resistor used to protect the DC power supply dissipates power. The pulsed modulator proposed for this design has the ability to self limit the current during arcing or shorted load faults. This protection is completely passive yet does not dissipate power during normal operation, increasing the system's efficiency. These types of protection schemes are generally not available with high-voltage DC power sources.

The design of the pulsed high-voltage source is based on a solid-state Marx architecture developed at LANL [2]. This paper describes the design, construction, and initial test results of a scaled prototype modulator for the IEC neutron source. The modulator prototype is scaled to 1/10th the output voltage of the final design to allow air insulated operation of the prototype.

II. PULSED MODULATOR DESIGN

The IEC neutron source under consideration requires a 120 kV, 10 A modulator. The pulse width is required to be variable between 50 μs and 1 ms at a duty factor up to 5%, resulting in a pulse repetition frequency ranging from 1 kHz – 50 Hz. The pulse droop required is < 5% at the longest pulse length.

A scaled prototype modulator was constructed to demonstrate the capabilities of the LANL solid-state Marx modulator. The scaled prototype has approximately 1/10th the output voltage but the same output current as the full-scale modulator. The characteristics of the demonstration modulator are contained in Table 1.

Table 1. Scaled-prototype modulator specifications.

Output voltage	13 kV
Output current	10 A
Voltage droop	< 5%
Peak power	130 kW
Pulse width range	50 μs – 1 ms
Pulse energy	130 J
Max duty factor	5%
Max average power	6.5 kW
Number of stages	10
Voltage per stage	1300 V

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14. ABSTRACT

This paper discusses the design and construction of a 1/10th scaled prototype pulse modulator for an IEC neutron source. The scaled prototype modulator has an output voltage of 13 kV and an output current of 10A. A significant feature of the modulator is that it has a variable pulse width (50 ìs 1ms) with < 5% droop at all pulse widths. The modulator operates with a duty factor up to 5% and has a maximum pulse repetition frequency of 1 kHz. Preliminary test results are given.

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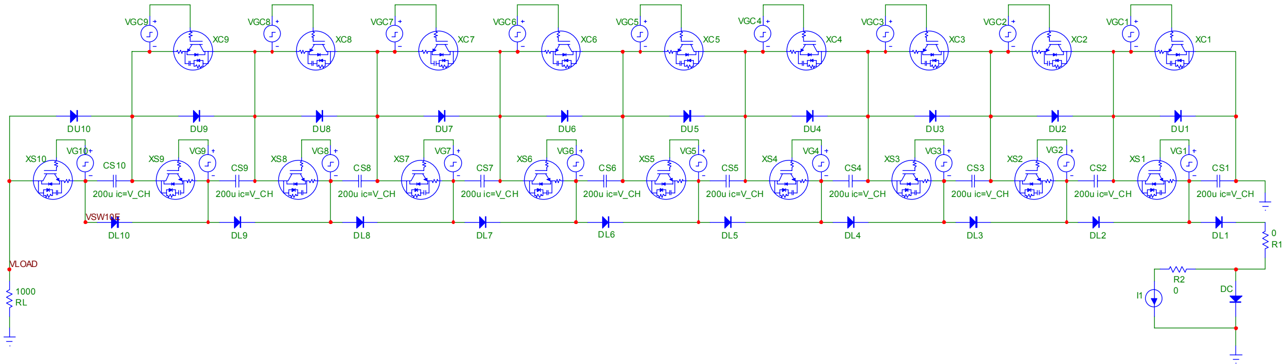

Figure 1. Electrical schematic of the 10-stage scaled prototype modulator used for SPICE modeling.

The scaled prototype modulator is a 10-stage solid-state Marx bank. A schematic of the solid-state Marx architecture is shown in Figure 1. The prototype modulator operates at a stage voltage of 1300 V/stage for a pulsed output voltage of 13 kV.

The LANL solid-state Marx modulator design follows a typical Marx topology except that the charging resistors have been replaced by diodes and the stage switches have been replaced by solid-state switches. In a modification to previous designs a second set of switches are placed in parallel with the upper charging diodes. These switches are open during the output pulse and are closed during the recharge process, giving the stage capacitors a path to ground during charging. The use of these stage charging switches replaces the charging inductor used in previous designs. This charging inductor would have become prohibitively large for the long pulse lengths required in this application.

A photo of the front of a single modulator board is shown in Figure 2. The stage (lower) and charging (upper) switches and their fiber optic triggering circuitry are shown. The IGBTs are mounted under heat sinks to the left of the center of the board. The two charging diodes are also shown in the lower center part of the board.

A photo of the back of a single modulator board is shown in Figure 3. Each stage contains a single 200 μF, 1500 V capacitor [3]. This capacitor provides the energy necessary to achieve < 5% droop during the long pulse length (1 ms) operation. A small ferrite transformer located in the center of the board is used to supply isolated utility power to the triggering system. The transformer's primary is a single high voltage wire threaded through the center of all 10 boards and is driven with an H-bridge inverter operating at 100 kHz.

A picture of the entire assembly of 10 boards is shown in Figure 4. The boards are supported by nylon all-thread rods with nylon spacers between boards. The assembly is mounted to three pairs of nylon feet. The entire assembly is 17.8 cm × 17.8 cm × 61.0 cm long, not including the height of the mounting feet.

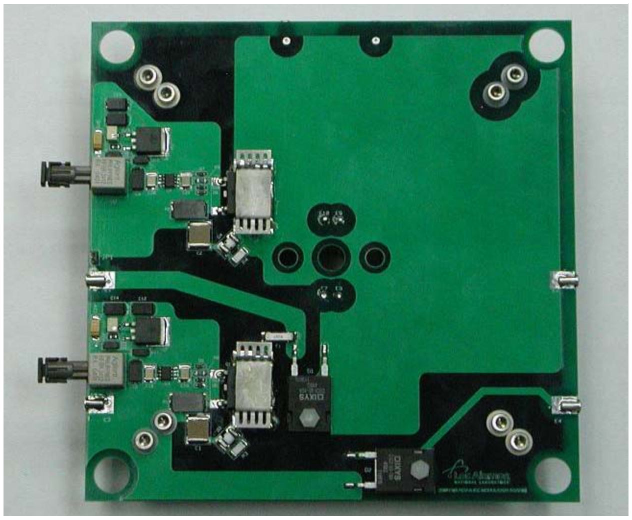

Figure 2. Front view of a single modulator board showing the switching and triggering circuitry. The boards are square and measure 17.8 cm (7 in) on a side.

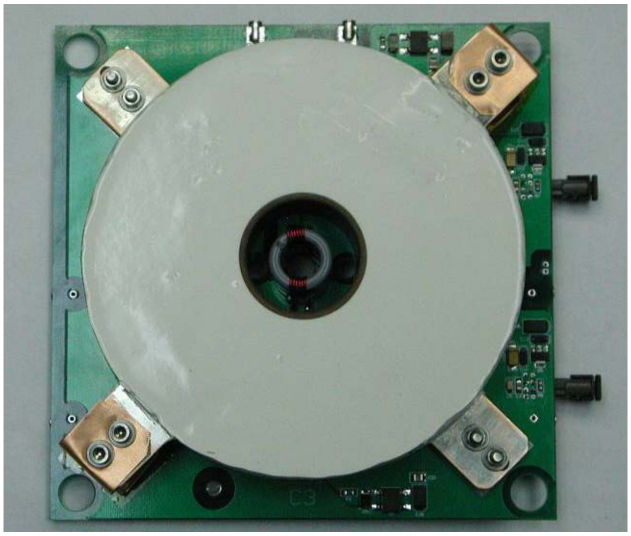

Figure 3. Back view of a single modulator board showing the stage capacitor and utility power system.

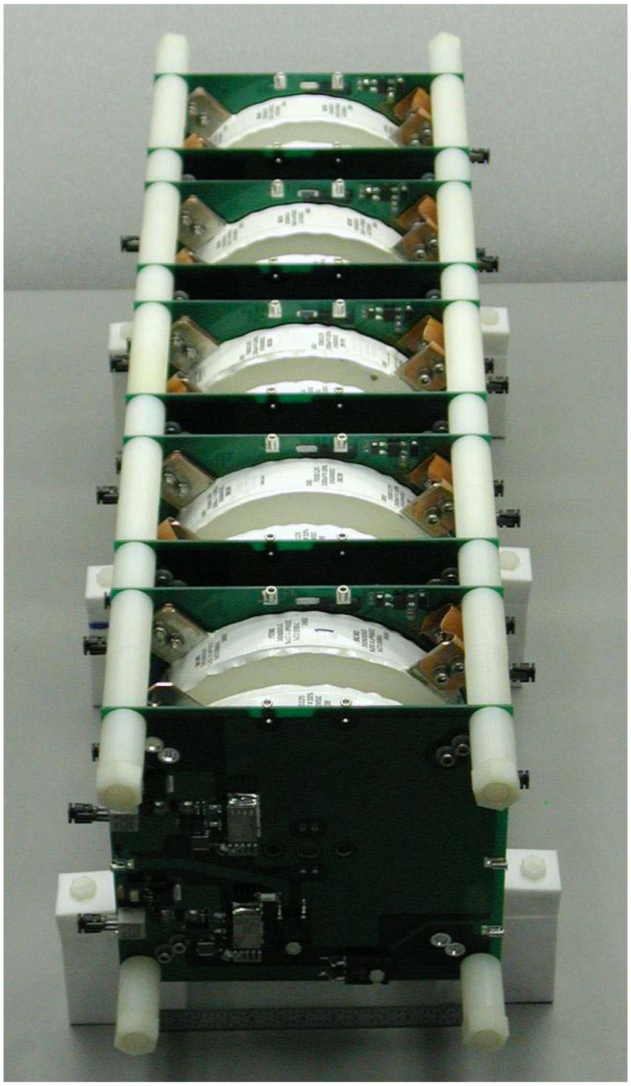

Figure 4. The scaled prototype modulator is a stack of 10 solid-state modulator stages each laid out on their own circuit board. the modulator operates at 1300V per stage for a pulsed output voltage of 13 kV.

III. DESIGN FEATURES

The use of all solid-state components in a Marx architecture provides many benefits. These benefits are briefly described in the following paragraphs.

Variable pulse length: The switches for each stage are controlled via fiber optic control signals, allowing independent control of the pulse width of each stage.

Variable amplitude: The ability to control the pulse width of each stage independently provides the capability of rapidly varying the output amplitude and can be used to create complex output waveforms. When used to power an IEC neutron source the variable amplitude capability can be used for rapid adjustment of the neutron intensity.

Variable pulse repetition frequency: The fiber-optic stage triggering allows the pulse repetition frequency to be adjusted on a pulse to pulse basis. The modulator can also be operated in burst mode, for a train of several pulses spaced very close together.

Transient switch over-voltage protection: The modulator has the inherent ability to protect the switches from voltage transients caused by inductive loads. This capability is called self snubbering, because it resembles the protection of a snubber but without the extra components or the power dissipation of a traditional snubber [4].

Over-current protection: The modulator uses emitter feedback to limit the switch current during an arc or a shorted load fault. This protection is passive, requiring no rapid intervention by the user or the control system. It is also efficient because the dissipative protection is only active when there is an over-current condition.

The design of the scaled prototype also includes several enhanced features. These enhanced features are described in the following paragraphs.

Long pulse length: The pulse length of this modulator is up to 1 ms with < 5% droop. Previous modulators of this design had pulse lengths on the order of 5 μs. This long pulse length with low droop was achieved by using 200 μF high-energy-density stage capacitors. There are 10 of these capacitors in the prototype modulator, each of which stores 169 J at a charge voltage of 1300 V per stage.

Inductorless charging: Previous modulators of this design used a charging inductor to complete the pathway between the stage capacitors and ground during charging. The long pulse length required of this modulator precludes the use of a charging inductor, since its size would be prohibitively large. For this design we used active switching to complete the charging pathway. The switches are controlled with fiber-optic trigger signals and are only on when the load switches are open.

Snubberless operation: This concept was explored in previous designs but this is the first design to fully implement the concept. Snubbers are generally designed for a given pulse width and load inductance. Being able to operate without snubbers improves this design's pulse-width variability and pulse repetition variability without limiting the protection given to the switches. Traditional snubbers also dissipate power and so snubberless operation improves efficiency. Since snubberless operation offers full switch protection independent of load inductance, the modulator can fire into almost any inductance without the worry of switch failure.

Stage fusing: A stage-isolating fuse was incorporated into this design. If a switch fails short the high current through the fuse will cause it to open. This will fully isolate the stage with the failed switch. The output from the remaining stages bypasses the isolated stage through the charging diodes.

High duty factor. Previous designs of this type were operated at a low duty factor of ~ 0.06%. This modulator is designed to operate at a significantly higher duty factor of up to 5%. The maximum duty factor of this design is only limited by the output current of the capacitor-charging power supply. The duty factor could be increased further by using a higher current capacitor charging supply.

IV. RESULTS

The following figures contain some preliminary test results from the scaled prototype modulator. These test results are for a stack of 2 boards fired into a 200 Ω load. The boards are completely snubberless in these tests.

The short pulse (50 µs) capability of the modulator is shown in Figure 5. This data is for a 2-stage stack fired into a 200 Ω resistive load. The charge voltage is 1300 V per stage for an output voltage of 2600 V. The output current is 13 A. Droop is negligible.

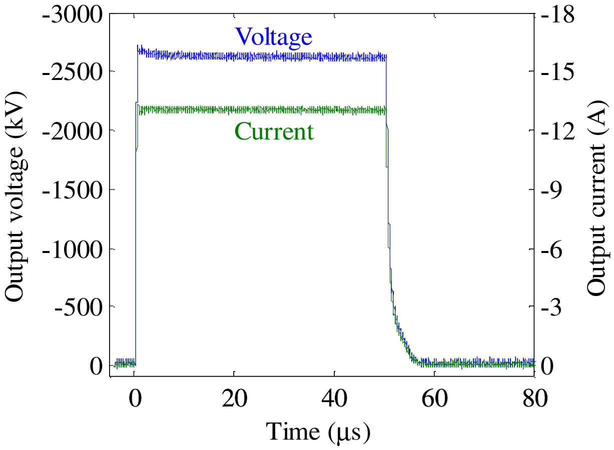

Figure 5. Short pulse (50 µs) operation of a 2-stage stack fired into a 200 Ω load. The initial charge voltage is 1300 V per stage.

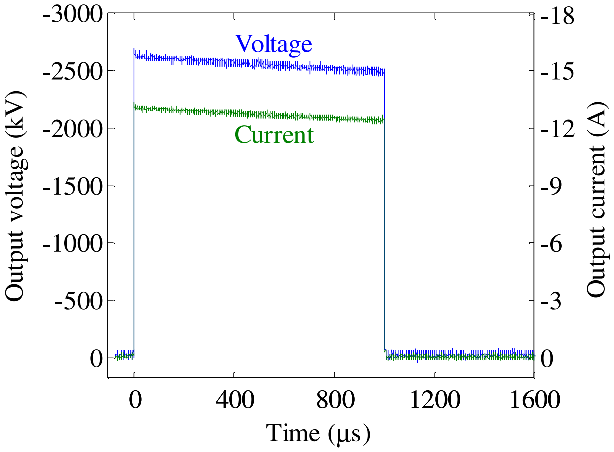

Figure 6. Long pulse (1 ms) operation of a 2-stage stack fired into a 200 Ω load. The initial charge voltage is 1300 V per stage.

The long pulse (1 ms) capability of the modulator is shown in Figure 6. This data is for a 2-stage stack fired into a 200 Ω resistive load. The charge voltage is 1300 V per stage for an output voltage of 2600 V. The peak output current is 13 A and the droop is ~ 4%.

The high duty factor capability of the modulator is shown in Figure 7. This figure contains the output voltage waveform for a 50 µs pulse operated at 1 kHz, which is a 5% duty factor. Four output pulses are shown.

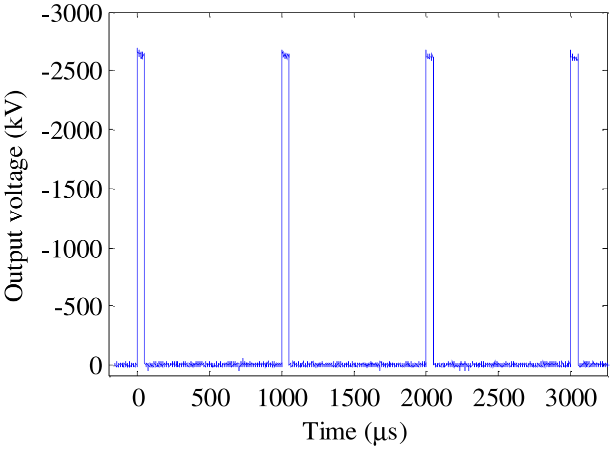

Figure 7. High duty factor operation of a 2-stage stack fired into a 200 Ω load. The pulse width is 50 µs and the device is operating at 1 kHz for a 5% duty factor, 4 pulses are shown. The initial charge voltage is 1300 V per stage.

In addition to the 200 Ω load an extra inductance of 22 µH was added to test the performance of the self snubbering. The 2-stage stack was able to fire into this inductance without damage even though there was no traditional snubber protecting the switches.

Each individual board as well as the 2-stage stack were fired into a short circuit for a pulse duration of 50 µs. The emitter feedback limited the fault current to 28 A and all boards were unharmed.

V. CONCLUSIONS

A scaled prototype modulator for an IEC neutron source was designed and constructed. The design followed a solid-state Marx architecture with actively switched charging. Using a pulsed solid-state Marx modulator to drive an IEC modulator will allow the neutron source to have multiple enhanced output capabilities such as single pulse, high-frequency burst, and continuous pulsed modes. The output amplitude and pulse width will also be adjustable on a pulse to pulse basis. The modulator design also offers several reliability enhancing features such as transient switch over-voltage protection, switch over-current protection and stage fusing.

Preliminary results for a 2-stage stack fired into a resistive load were shown. All tests were performed without traditional snubbers protecting the switches. The boards are protected against a short circuit fault by emitter feedback and the fault current under these conditions is limited to 28 A. An inductance of 22 μH was added to the 200 Ω load and the 2-stage stack was fired into it without switch failure.

VI. REFERENCES

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