DEVELOPMENT OF A 300-KV SOLID-STATE MODULATOR FOR AN ARGONNE XFELO INJECTOR*

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Abstract

A high-voltage, solid-state, switched modulator is presently being developed at Argonne National Laboratory (ANL). A Marx architecture, which charges capacitors in parallel and discharges them in series, has been utilized in the design of the modulator. This power system will have the capability of providing a 300-kV pulse with 0.5-µs rise time, 1-µs fall time, a 5-µs pulse flat top, and up to 10 Hz repetition rate. This modulator is designed to operate a pulsed, low-emittance thermionic prototype gun, which is needed for feasibility studies of Argonne's x-ray free-electron laser oscillator (XFELO) injector. This paper presents an overview of the design and development of the XFELO injector's pulsed gun modulator, together with preliminary test results.

INTRODUCTION

The pulsed power modulator was designed to supply cathode and filament voltage to a pulsed thermionic prototype gun. In order to reduce the initial emittance of the gun, a single-crystal CeB_6 cathode with a 3-mm diameter will be used in the gun design.

The design parameters of the modulator are listed below.

Output voltage:	up to 300 kV
Load current:	up to 300 mA
Load capacitance:	200 pF (estimated)
Pulse width:	up to 5 µs (adjustable)
Pulse droop:	< 0.3%
Rise time:	< 0.5 µs
Fall time:	< 1.0 µs
Pulse repetition rate:	up to 10 Hz.

The very small physical dimensions of the cathode limit the amount of energy that may be dissipated during possible arcing in the gun, on or near the cathode, without causing serious damage to the cathode. Special measures were implemented to limit the arc duration and the peak current.

Charging and discharging the pulsed thermionic gun's capacitance required the modulator to produce a short-duration (≈ 500 ns), 200-A pulse with fast front and trailing edges.

The design of the modulator is based on a solid-state Marx architecture that utilizes Insulated Gate Bipolar Transistor (IGBT) devices in both charging and discharging circuits.

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MODULATOR DESIGN

A simplified block diagram of the modulator is shown in Figure 1.

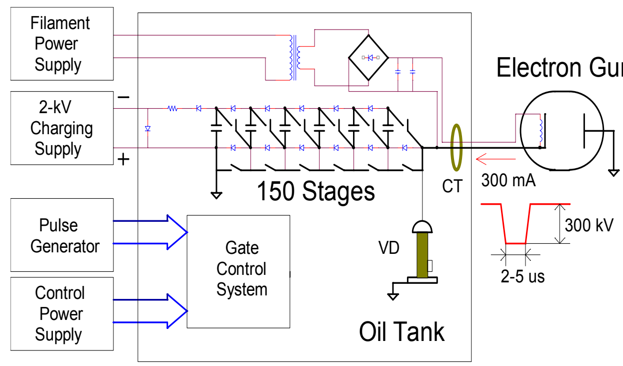

Figure 1: Simplified block diagram of the modulator.

The modulator, a 150-stage Marx generator utilizing IGBT switches for both charging and discharging circuits, operates at a voltage of 2 kV/stage for a pulsed output voltage of 300 kV. Two sets ("main" and "charging/crowbar") of IGBT switches, model IXGF30N400, are used in operation of the modulator. The modulator consists of 25 identical 6-stage PC boards (see Figure 2), connected in series.

The main switches (MS) are closed during the pulse, connecting all stage capacitors in series and providing a summation of the stage voltages to the load.

The charging/crowbar switches (CS) are open during the pulse, but they are closed after the pulse to quickly remove high voltage from the gun at the pulse's fall time or after the detection of load arcing. This also provides the stage capacitors a path to ground during the charging period. Several 10-Ω resistors connected in series with each CS provide load current limitation and snubbing of possible oscillations associated with stray inductance and capacitance of the equipment components.

Each switch is controlled by a separate gate driver connected via a fiber optic cable to a control and monitoring chassis. The fiber optic control system was used to minimize any stray capacitance within the system. To minimize the Miller effect, the gate drivers apply -12 V to the IGBT switch gates. IGBT switch conduction is controlled with a +12-V voltage applied to the IGBT gates. These gate driver voltage levels were chosen to (1) ensure complete and fast shutting off of the switches and (2) limit the switch current to about 200 A in the conducting state.

Gate driver control power is supplied through a set of isolating, toroidal ferrite transformers (one transformer per 6-stage PC board). Each transformer has a single-turn primary and twelve 2 × 25-turn secondary windings.

The 25 primary windings are connected in series; an amplified 20-kHz signal generator was used as a source to the transformer primary.

A variable alternating current (AC) power supply with a 350-kV isolating step-down transformer and a rectifier provides filament heater power to the gun. An oil tank houses all the high-voltage components, a voltage divider, a current transformer, and the auxiliary components.

TESTING 6-STAGE PC BOARDS

Due to high-voltage isolation issues, testing only culminated with the 6-stage PC boards. Each board controls 1/25th of the output voltage, yet each has the same peak output current during charging and discharging of the load capacitance as the full-scale modulator. All 25 PC boards (plus two additional spares) were built and tested at full voltage (12 kV at the board output).

The test set-up block diagram is shown in Figure 3.

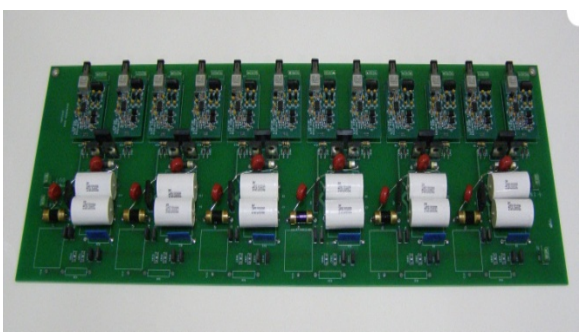

Figure 2: The 6-stage PC board.

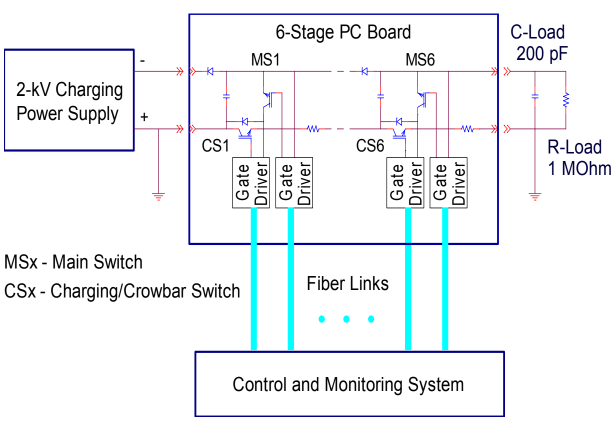

Figure 3: The 6-stage PC board test set-up.

The output voltage waveform is presented in Figure 4.

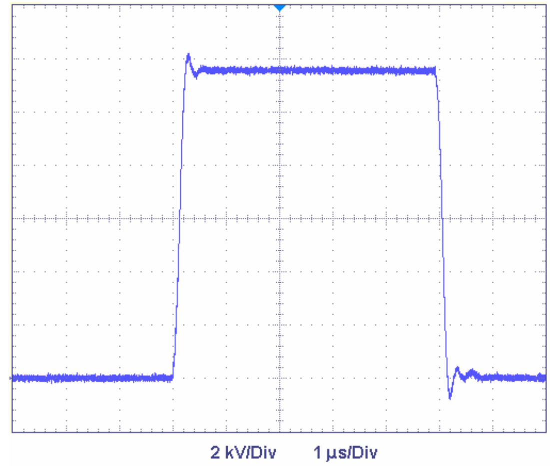

Figure 4: 12-kV 6-stage output voltage.

Both front and trailing edges of the pulse were measured to be 300 ns in duration. Minor oscillation at the pulse edges is present because the total dumping resistance of one PC board is only 60 Ω. The resistance in the fully assembled modulator is designed to be 1.5 kΩ, which is enough to damp down the pulse edge oscillation.

The load current is plotted in Figure 5. The first current pulse corresponds to charging the load capacitance through the main switches. The second one represents quick discharging of the load capacitance through the crowbar switches.

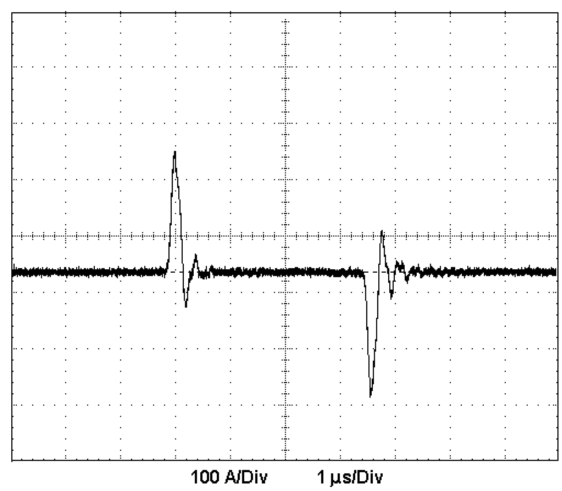

Figure 5: Load current.

Each 6-stage PC board was tested at a 10-Hz repetition rate. Voltage droop was practically undetectable since effective capacitance of one PC board is 25 times greater than the one of the entire modulator.

ARC PROTECTION

The total maximum amount of energy dissipated during a gun arc event is $E_T = E_G + E_D$, where E_G is the energy accumulated in the gun capacitance C_G, and E_D is the energy delivered from the modulator.

The maximum contribution from E_G is $E_G = C_G V^2/2 \approx$ 10 J, with the gun capacitance $C_G \approx 200$ pF and at V = 300 kV.

When all the modulator capacitors are completely discharged during the arc and with an effective modulator capacitance C_M = 2 nF at V = 300 kV, the calculated maximum $E_D = C_M V^2/2 \approx 90$ J.

An additional cathode protecting scheme must be implemented to prevent destruction of the cathode when dissipating E_T = 100 J.

One solution is to quickly turn off the main switches and/or turn on the crowbar switches, after an arc is detected. However, the measured total time delays in the IGBT circuits are as follows:

Turn off: ≈ 700 ns,
Turn on: ≈ 1200 ns.

Before the main switches are turned off, as much as 37 J will be delivered from the modulator, and the total dissipated energy will be as large as 47 J. This may not be considered acceptable, either.

The solution we offer is based on the fact that the load current during the pulse flat portion is only 300 mA. Therefore, there is no reason to keep the IGBTs of the main switches capable of conducting 200 A during this period of time. Lowering the gate voltage from +12 V to +6 V after the gun capacitance is charged (see Figure 6) will lower the maximum possible main switch IGBT's current to as low as ≈ 20 A; the amount of energy delivered from the modulator before it turns off will be only ≈ 4.2 J, which may be considered acceptable.

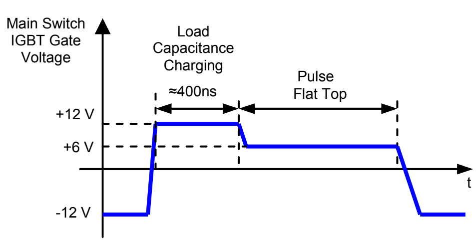

Figure 6: Proposed main switch IGBT gate voltage waveform.

CONCLUSION

The design of a pulsed, solid-state, Marx-architecture-based modulator for the Argonne XFELO feasibility study has been presented. This modulator is composed of 6-stage PC boards; 25 PC boards in series are used to generate a 300-kV pulse at a 10-Hz repetition rate. Initial testing of each of the 6-stage boards has demonstrated that a 5-μs flat top pulse at 10 Hz was achieved with repeatability.

A pulsed thermionic gun arc protection scheme has been developed that controls the IGBT gate voltage to decrease possible current flow into an arc. Design benefits of this power system consist of having modular subassemblies, low stored energy, fast rise and fall time, and negligible pulse droop.

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