A HYBRID SOLID-STATE INDUCTION MODULATOR WITH PULSE TRANSFORMER TO DRIVE SLAC KLYSTRONS[*]

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Abstract

A solid state hybrid induction modulator has been built and tested which can replace the line type modulators currently in use to power SLAC klystrons. The modulator uses twenty-two IGBT modules to drive eleven single turn primary windings of a transformer in parallel. Passing a pipe through the center of the vertically stacked METGLAS cores forms the single turn secondary. One end of the secondary winding is tied to ground, while at the output an induced voltage of eleven times the primary charge voltage is produced. The modulator in turn powers a conventional SLAC high voltage transformer and klystron. The output voltage produced by the "short stack" modulator built at SLAC is 24 kV, with a current of 6000 A. Pulse widths of up to 3 μs, at 120 Hz can be produced. Design details, test data, and comparisons with the conventional line type modulators will be presented.

I. INTRODUCTION

The two mile long linear accelerator at SLAC uses RF driven accelerator sections to accelerate electron and positron beams up to a maximum of 55GeV. Each accelerator section is driven by a SLAC 5045 klystron. There are 244 klystrons in the Linac, and a line type modulator powers each one; see Table 1 for klystron modulator specifications. The modulator has a pulse forming network (PFN) with tunable inductors, and it is charged to 46.7kV and discharged through a thyratron into a 1:15 pulse transformer in a pulse tank at the base of the klystron. The modulator generates a pulse of 23.3kV, 6kA at 120Hz. The modulator reliability is strongly tied to the operation of the thyratron [1]. Many man-hours are spent ranging thyratron reservoirs and tuning PFNs. If the thyratron switch is replaced with an IGBT, then a PFN is no longer needed to form a square pulse. A modulator with neither a thyratron nor a PFN can significantly reduce the needed manpower to maintain the Linac modulators.

The PFN modulators at SLAC were designed in the 1960s and improved in the 1980s. At the time, thyratrons were the only viable switch for this high peak power system (145MW). In recent years, high power solid-state switches have become more available—particularly IGBTs. As more power modulators are converted to solid-state switch designs, the thyratron market will fade, and SLAC could have some difficulty in maintaining the Linac as it exists today. A solid-state klystron modulator design may keep SLAC performing valuable physics research in the years ahead.

PFN Voltage	46.7 kV
Thyratron Anode Current	6225 A
Pulse Transformer Ratio	1:15
Voltage Pulse Width	5 μs (ESW)
Pulse Rise Time	0.8 μs
Pulse Fall Time	1.8 μs
Pulse Repetition Rate	120 Hz
Nominal PFN Impedance	4 Ω
Average Power	87.2 kW

Table 1. SLAC Line Type Modulator Specifications

II. SOLID-STATE MODULATOR DESIGN

For the past several years, SLAC, LLNL, and Bechtel Nevada have been pursuing a solid-state modulator design for the Next Linear Collider (NLC) [2]. In support of that effort, a smaller modulator was constructed using pieces from the NLC modulator design to drive a SLAC 5045 klystron [3]. This modulator, often referred to as the Short Stack modulator, consists of eleven sections (cells) of double driven metglass cores stacked to form an 1:11 transformer with eleven independent and grounded primary turns and a single secondary turn. Two core driver boards—one master and one slave, drive each primary turn. Figure 1 shows an encapsulated METGLAS core with two core driver boards. A core driver board consists of an IGBT, an IGBT gate driver, energy storage

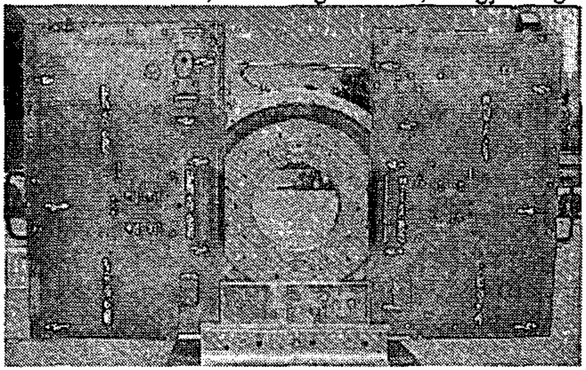

Figure 1. Encapsulated METGLAS core with Core Driver boards.

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capacitor, energy recovery diode and capacitor, and a core reset driver (on the master board only)[4]. See Figure 2 for the cell schematic. The cells have a low inductance, and the IGBT gate drivers are designed such that the collector to emitter current of the IGBT has a high di/dt.

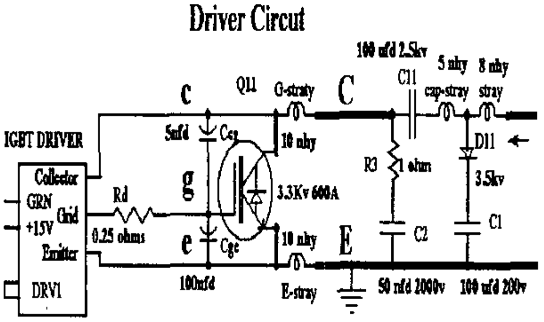

Figure 2. Core Driver Circuit

III. MODULATOR TEST SETUP

The short-stack modulator is mounted on a bench top with the pulse cable mounted through the bottom of the bench table. The inner conductor of the cable is connected to a pipe within the inside diameter of the core assembly. The gap between the pipe and the core assembly was minimized to reduce the leakage inductance of the transformer, and it was filled with a silicone jell to serve as an insulator. The cable is an Isolation Designs tri-axial cable; the same cable used with the PFN modulator. The modulator is enclosed in a metal box with door access to both ends of the table to allow for driver board diagnosis and replacement. Figure 3 is a photograph of the solid-state modulator in its enclosure along with the power rack and klystron; not pictured is the 150kW power supply that provides the 2.2kVDC voltage used to charge the energy storage capacitors of the twenty-two core driver boards. The air internal to the enclosure is circulated with fans, and its temperature is stabilized by the core temperature. The cores are water cooled by 90°F klystron gallery LCW used to cool the klystrons. The klystron's interlocks remain the same as administered by the Modulator Klystron Support Unit (MKSU). The PFN modulator trigger is adapted to provide an adjustable pulse width trigger. The pulse width limit is a function of the volt-second limit of the core. A block diagram of the complete test setup is found in Figure 4.

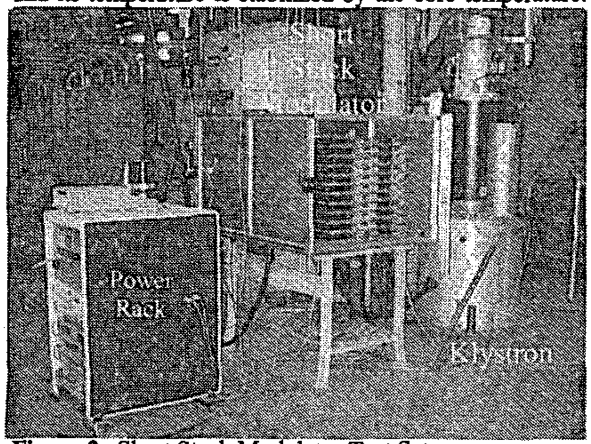

Figure 3. Short Stack Modulator Test Setup.

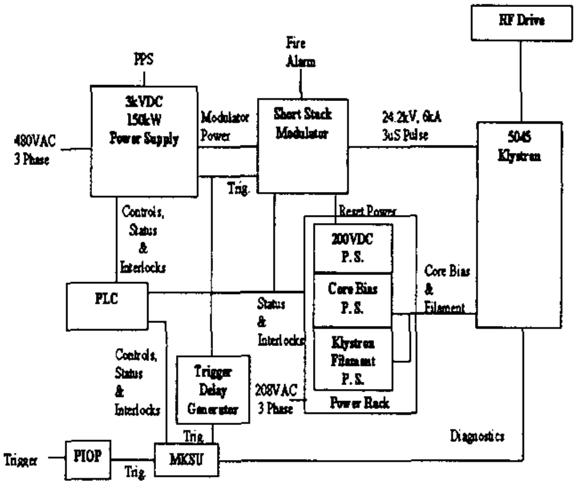

Figure 4. Test Setup Block Diagram

IV. TEST RESULTS

The modulator was connected to the 5045 klystron and run up to 2.2kV per cell with the results below in Figure 5. The beam voltage attained an amplitude of 330kV. This signifies that only ten of the eleven cells were working at the time. The problem was repaired at a later date, but not before the all of the data within this paper was recorded. Therefore, all of the data recorded in this paper reflects the operation of ten cells only. The induction modulator design is very flexible in that it is easily expandable and it will still operate in the event of the demise of any number of cells.

The pulse rise time is on the order of 2μs. The rise time of the beam voltage pulse from the short stack modulator is slower than that of the line type modulator presumably because the PFN voltage is twice the short stack voltage. For the same inductance (leakage inductance of 1:15 transformer), twice the voltage results in half the rise time. Therefore, the rise time of the beam voltage pulse from the line type modulator is half the rise time from the short stack pulse. The pulse width is limited by the volt-second limit of the cores; some cores in the stack have a volt-second limit of 6mVs. If the cores saturate, then there is a short circuit condition in which the current in the IGBT increases substantially which may damage the switch. The cores are pulse reset before every shot.

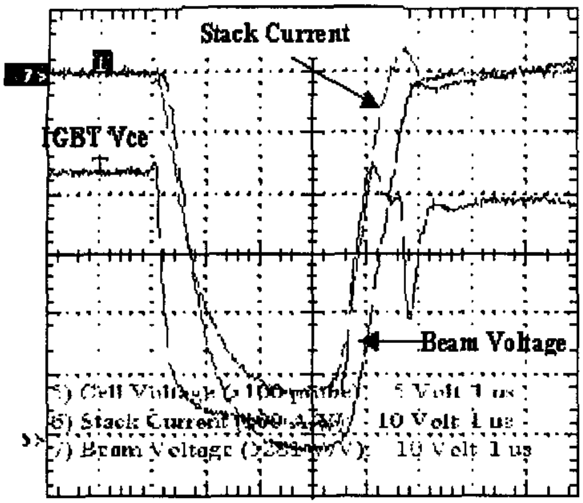

Figure 5. Short Stack Pulse into 5045 Klystron.

Another test was set up to determine how the modulator performs in the event of an arcing load. It is presumed that the klystron will arc on occasion, thus the modulator must not fail when the load arcs. The modulator pulse cable was connected to a 4Ω load with a parallel triggerable spark gap. The modulator was triggered first, followed by a trigger to the spark gap at different delays. Measurements were made with the arc occurring early in the pulse, mid pulse, or late pulse. Early arcs resulted in the largest peak load currents. Figure 6 is data taken from an arc occurring early in the pulse. The upper most wave shape is the stack current that peaks at 6kA. The other two wave shapes are the Vce of IGBTs for two different cells. This data was taken while Mitsubishi 4.5kV IGBTs were installed in the modulator. No IGBTs failed under any of the arc conditions. Further tests will be performed with EUPEC 3.3kV IGBTs installed.

Full power tests were performed to determine the heating of the critical components; all of the following tests involved EUPEC 3.3kV IGBTs. The modulator was connected to the klystron, and it was operated at full voltage and a repetition frequency of 120 Hz. A thermal imaging camera was employed to view the temperatures of the components within the short stack enclosure. Figure 7 is a thermal image of the short stack looking straight in at the core driver boards. The hottest components were found to be on the core reset board; up to 90°C. The core reset boards were later modified to reduce the component heating. The IGBT heat sinks are mounted at right angles to the water cooled cores. Therefore, the temperature of the heat sinks is greatest near the short stack enclosure doors; the place measured by the thermal camera. The highest measured temperature at the heat sink is 65°C. The heat sinks are connected to the water cooled core stack by two rods with nuts. When the nuts are tightened, a flat surface on the heat sink makes contact with the water cooled core; there is no thermal compound at the junction. Later bench tests with the heat sink and various thermal compound materials showed that the temperature on the heat sink can be reduced by as much as 5°C depending upon the thermal compound employed.

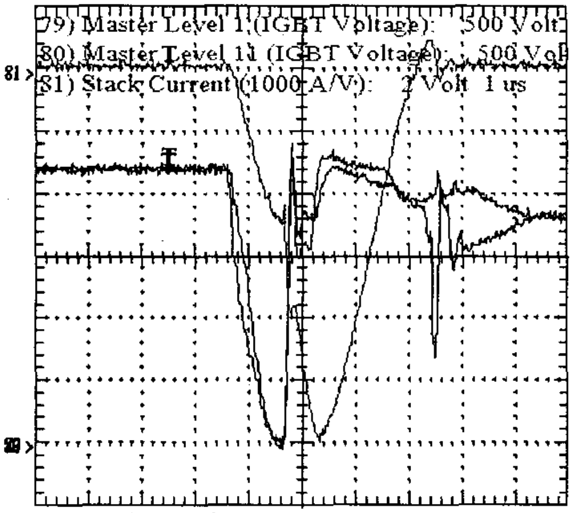

Figure 6. Arcing Load Data.

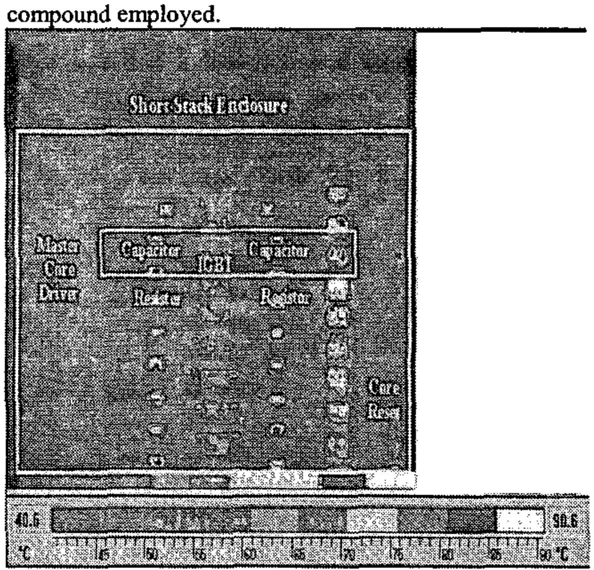

Figure 7. Short Stack Thermal Image at Full Power.

Thermocouple wires were installed into key locations within the modulator to monitor the following temperatures: cabinet air, water supply, water return, ambient air, short stack IGBT heat sink, power supply IGBT heat sink, and short stack core temperature. The modulator was operated at full power for 90 minutes, until the temperatures began to stabilize, and then it was turned off in order to measure the thermal time constants. Figure 8 has the test results. The short stack IGBT heat sink had a measured temperature of 57°C; consistent with the thermal image since the thermocouple is mounted midway between the end of the heat sink and the core. The difference in temperature between the heat sink and the core as measured by the thermocouple is 17°C. The difference from one end of the heat sink to the core end is 25°C. The core temperature tracks the return water temperature, and the return water temperature is only 4°C warmer than the supply water. The cabinet air temperature peaked at 44°C.

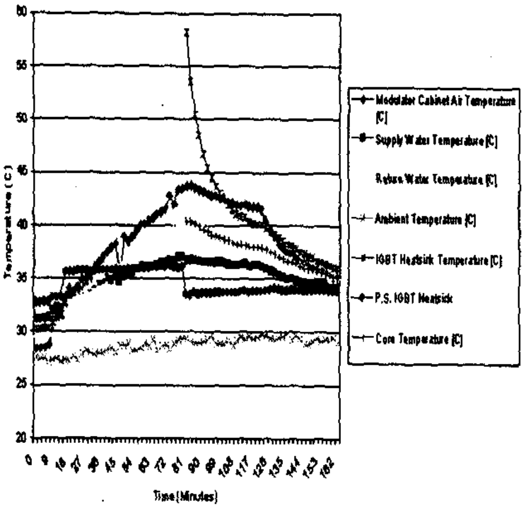

Figure 8. Short Stack Thermocouple Measurements at Full Power.

V. CONCLUSIONS

The short stack modulator testing is demonstrating that a solid-state design for a power modulator to drive high power klystrons like those used at SLAC is viable. More testing is essential to work out the design details. A larger core is needed per cell to generate the desired pulse width. A longer pulse width will increase the component temperatures, thus a more careful thermal design is imminent. As more IGBTs become available, continued switch evaluation may lead to further improvements of the modulator performance.

VI. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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