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A SOLID STATE MODULATOR FOR DRIVING SLAC 5045 KLYSTRONS*

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Abstract

A test is ongoing at the Stanford Linear Accelerator Center (SLAC) where a solid state induction modulator is driving a SLAC 5045 klystron. The modulator generates 22 kV, 6 kA pulses that are stepped up by a 15:1 transformer that is a part of the klystron's pulse tank. The modulator's pulse duration is adjustable up to the volt-second limit of its cores, and it is capable of a pulse repetition frequency up to 120 Hz. The modulator's design, construction, and experimental results are the focus of this paper.

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; see Table 1 for klystron parameters. There are 244 klystrons in the Linac, and a thyratron modulator powers each one. 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 15:1 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.

Klystron Frequency	2856 MHz
Klystron Beam Voltage	350 kV
Klystron Beam Current	414 A
Microperveance	2
Peak Power Out	67 MW
RF Pulse Width	3.5μs

Table 1. SLAC 5045 Klystron Specifications

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 (150MW). 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.

II. 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 10-Stack modulator, consists of ten sections (cells) of double driven metglass cores stacked to form a 10:1 transformer with ten independent and grounded primary turns and a single secondary turn. Two core driver boards—one master and one slave, drive each primary turn. A core driver board consists of an IGBT, an IGBT gate driver, energy storage capacitor, energy recovery diode and capacitor, and a core reset driver (on the master board only). See Figure 1 for the cell schematic and Figure 6 for the ten stack modulator 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.

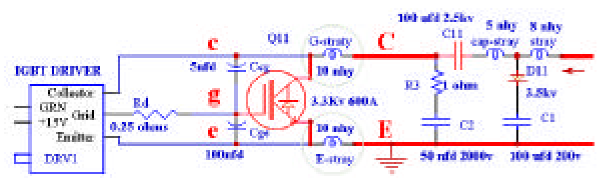

Figure 1. Core Driver Circuit

III. CORE DRIVER CONSTRUCTION

A. IGBT

The IGBT is a Eupec FZ800R33KF1. It is a 3.3kV, 600A device, and it was chosen for its high voltage rating, fast switching times, and for the absence of a turn-off tail. Higher voltage IGBTs are available, and they are being considered for future designs. The higher the voltage of the IGBT, then the fewer the cells needed to get the

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required output voltage; this may reduce the overall modulator cost.

B. Energy Storage Capacitor

The energy storage capacitor is a segmented, metalized polypropylene capacitor manufactured by NWL. It is 12.5uF, 5kV, and low inductance. There are two capacitors per core driver board. A capacitor with a high energy density is desirable so to minimize the pulse droop. The peak current in each capacitor is 1500A for 3µs at 120Hz. If the pulse droop is significant, then extra cells are needed in the modulator for droop compensation.

C. *Core*

There are three different types of cores used in the 10-stack modulator. The most numerous is the National Arnold 2605SA1 Metglass core with Namalite insulation. There are also some Hitachi FT-2M Finemet cores and some National Arnold CRMW2 nano-crystalline cores. All of the cores have the same dimensions: 7.25”ID, 14.75”OD, and 1.5”Ht. The core fits into an assembly that forms the primary winding of the transformer. The assembly includes a coil of tubing which provides the necessary cooling for the core and the IGBTs. On the outside diameter of the assembly are two flats where the IGBT heat sinks make contact. The core is potted into the assembly to provide the necessary insulation for operation. When two core assemblies are stacked, there is a notch wide enough for the core driver boards to slide into place and make electrical contact with the primary winding.

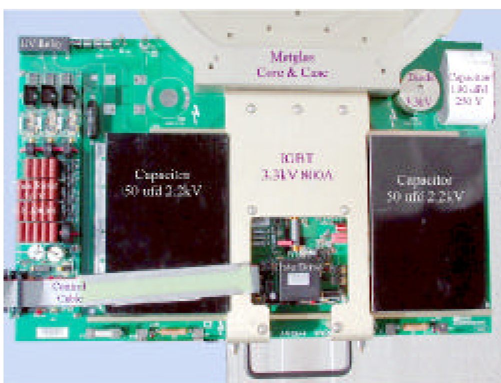

Figure 2. Driver board with partial view of core case.

D. Diode

The diode is a Westcode SM35HXC103. It is a 3.5kV diode with a Q_{rr} of 33µC. The diode is mounted in an aluminum can to minimize its inductance. The can has a spring washer inside to maintain the necessary pressure on the diode. When the IGBT turns off, the diode must turn on quickly to direct the energy stored in the circuit’s inductance and the core’s magnetizing current into the energy recovery capacitor. The diode inductance and forward recovery should be minimized, since any added voltage during the diode’s turn on will add to the voltage on the energy storage capacitor and possibly damage the IGBT. The diode must also have a low Q_{rr} if the cell will be used for droop compensation.

E. Energy Recovery Capacitor

The energy recovery capacitor is a 130uF, 250V capacitor used to store the energy from the core when the IGBT turns off. This capacitor, like the diode, must be low inductance to protect the IGBT. The capacitor is charged to 200VDC to aid the energy capture. The 200VDC input is also used to charge the core reset driver capacitor bank.

F. Core Reset Driver

The core is reset with a 200V, 100A pulse prior to the main trigger pulse. The driver consists of a capacitor bank, series IGBTs, and control circuitry. The main trigger for a cell will only commence if the reset current exceeds a measured threshold.

G. IGBT Driver

At the core of the IGBT driver is a Concept Driver. A booster circuit made of a capacitor and a fast SCR assists the Concept Driver to improve the turn on characteristics of the IGBT. For a thorough description of the IGBT driver circuit, refer to Reference [4].

H. Trigger Distribution

The trigger distribution board fans out one of two trigger inputs into any of the ten cell’s master core driver boards. The core reset is triggered first. If the core reset on a cell is sufficient, then the trigger distribution board triggers the master and slave core driver boards. The second trigger input on the trigger distribution board may be used as a delayed trigger for a droop compensation cell. The board also provides trigger diagnostics through a series of LEDs.

IV. MODULATOR TEST SETUP

The ten-stack modulator is mounted on a bench top with the pulse cable mounted through the bottom of the bench table and the center conductor running through the inner diameter of the stacked cores. The cable is an Isolation Designs tri-axial cable ten feet in length; the same type of cable used on the PFN modulator but twice as long. 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. The air internal to the box 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 PFN modulator provides the pulse transformer’s core bias, the klystron heater power, and some interlocks. The klystron’s interlocks remain the same. The modulator DC power comes from a SLAC built 3kV, 150kW power supply. The AC source for the power supply is tapped from the PFN modulator after the contactor, such that the modulator’s interlocks are still in effect and the personnel protection for the Linac is not violated. 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.

Figure 3. Ten-Stack Modulator (in foreground) with the PFN Modulator and 5045 Klystron.

V. TEST RESULTS

After the ten-stack modulator was assembled, it was tested into a resistive load. A 3.3Ω resistor was installed in the inner diameter of the stacked cores to minimize the inductance. The test results are given in Figure 4. The modulator was then installed in the klystron gallery to drive a SLAC 5045 klystron via the pulse cable. In Figure 5, the solid state modulator pulse is compared with the PFN modulator pulse. There are three noticeable differences between the two pulses; the rise time of the solid state modulator pulse is slower than the PFN modulator pulse, the pulse width is narrower, and the amplitude is lower.

In this case, the pulse rise time is limited by the circuit inductance. The test into the resistive load shows that the IGBT is capable of high di/dt. Circuit inductance is higher for the klystron test because of the inductance of the pulse cable, the leakage inductance of the pulse transformer, and because of the increased inductance of the ten-stack transformer that occurred when the resistors were replaced with the cable in the center of the ten-stack.

The pulse width is a function of the volt-second limit of the cores. The Finemet cores have the lowest volt-second limit (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 maximum operating voltage of a cell and the number of cells limits the pulse amplitude. The maximum voltage for this circuit is 2.2kV, thus the pulse amplitude for the ten-stack is only 22kV. The rated IGBT voltage with respect to the operating voltage limits the cell voltage and the forward recovery of the diode as discussed previously.

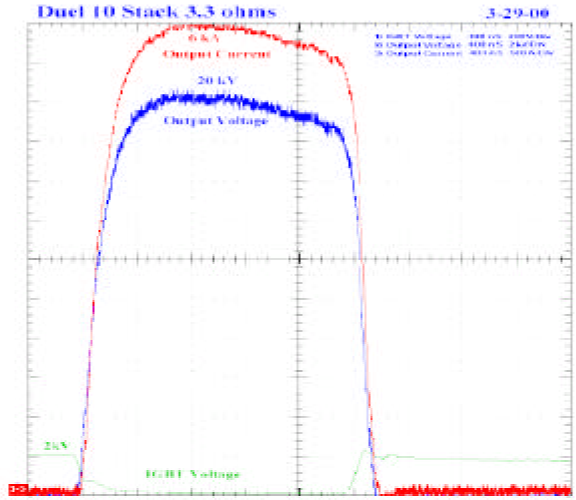

Figure 4. Ten-Stack Test Results into 3.3 Ohm Load.

VI. NEXT STEPS

The modulator will undergo some modifications before it is reinstalled in the klystron gallery. An eleventh core will be added so the modulator can get to the full voltage and, since each cell will run at a slightly lower voltage, the volt-second limit will be increased. Then the inner diameter of the stack will be redesigned to reduce the inductance. Also, the PFN modulator will be removed which will allow for a shorter pulse cable from the solid state modulator. These changes will improve the performance of the modulator, and allow for further operation as an active element in the klystron gallery.

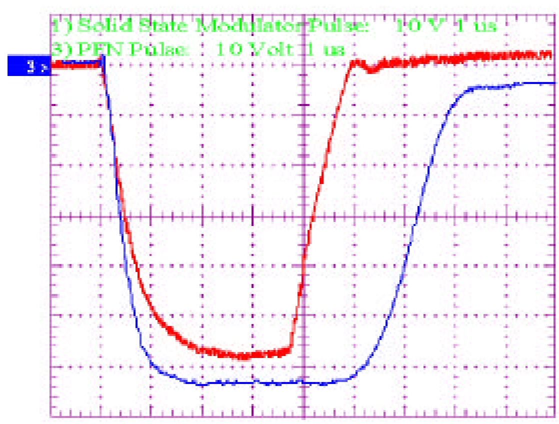

Figure 5. Ten-Stack Test Results into a 5045 Klystron

VII. ACKNOWLEDGEMENTS

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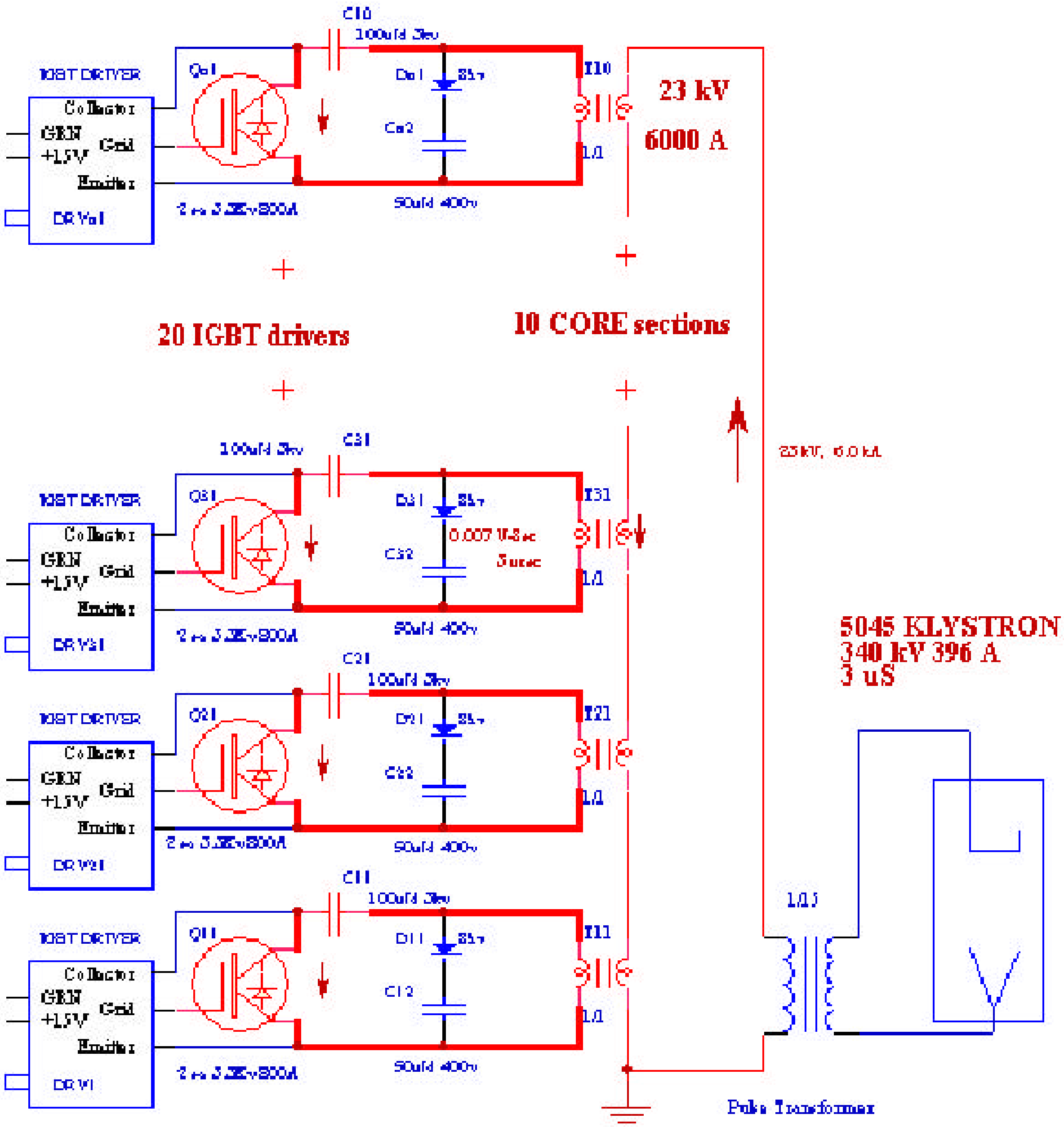

Figure 6. Ten stack modulator schematic.

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