A Second Long Pulse Modulator For TESLA Using IGBTs

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Abstract

A second and third modulator are being built at Fermilab to drive the klystrons for the TESLA Test Facility. These modulators are similar to one previously built at Fermilab. However, there are two differences. First, the new modulators are designed for a 10 MW multi-beam klystron under design by Thomson. Second, IGBT switches are being used in place of GTOs. The development of the series IGBT switch to replace the GTO switch is the most significant challenge. IGBTs have the advantages of lower gate drive and shorter turn off delay time.

INTRODUCTION

In 1994, Fermilab designed and built a modulator [1] for use at DESY's TESLA Test Facility (TTF). This modulator has been in operation for the past two years, driving a Thomson TH2104C klystron at up to 5 MW RF output. Future RF stations at TTF are expected to use a new high efficiency 10 MW multi-beam klystron (MBK) being developed by Thomson. The new klystron requires a modulator with higher peak power but with a shorter pulse length and the same average power. The original and new modulator requirements are shown in Table I.

Table I

	Original Modulator	New Modulator
Pulse Width (+/- 0.5%)	2.0 ms	1.4 ms
Output Voltage	130 kV	110 kV
Output Current	95 A	130 A
Repetition Rate	10 pps	10 pps

Fermilab is building two new TESLA II modulators which meet these new requirements. The new modulators use the original circuit topology, Fig. 1, but have some component changes.

The pulse transformer, the bouncer choke and the switch elements are the only major changes. The pulse transformer and bouncer choke changes are component value modifications to meet the new output requirements. The transformer has been changed from a 1:13 ratio to a 1:12 ratio and the bouncer choke has changed from 600 µH to 330 µH. This paper will focus on the new switch design because this was the most challenging aspect. The switch was a based on GTOs (Gate Turn Off thyristors) but is now based on IGBTs (Insulated Gate Bipolar Transistors).

IGBT VS. GTO

Our reasons for developing an IGBT switch were twofold. First, we wanted to develop some expertise with these newer components and to determine if they would have advantages over the GTO design. Second, the GTO switch in the new modulator would have had to turn off in excess of 2.3 kA under fault conditions, and we felt this was too close to the 3 kA maximum rating. As a basic switch, the IGBT is an easier device to use. The insulated gate requires a drive circuit to drive only a capacitive load. Gate drive peak power and average power are each approximately five times lower for the IGBT than for the GTO. The peak current rating of an IGBT is also the maximum current the device can interrupt in contrast to the GTO. The packaging of the GTOs is typically in easily cooled and stacked puck form in comparison to the heat sink mounting of IGBTs. Finally, the IGBT has approximately one tenth the turn on and turn off times of a GTO. This is not always a benefit however as the faster transients cause more EMI problems that must be dealt with. Selection of the devices was based on the requirements of the pulse transformer primary circuit. The switch assembly must conduct a 1.6 kA pulse for 1.7 ms and block 10 kV in the off state.

The final IGBT switch, shown schematically in Figure 1, consists of 15 Eupec FZ 1200R16KF4 devices. These devices have a forward blocking rating of 1600 Volts, an average current rating of 1200 Amps and a peak current rating for a 1 ms pulse of 2400 Amps. We chose the devices because they were the highest voltage devices then available with a 1200 A rating.

The assembly consists of twelve series IGBTs forming the main switching element plus three more IGBTs forming a backup switch. The backup switch is for protection of the klystron in the case of a main switch breakdown.

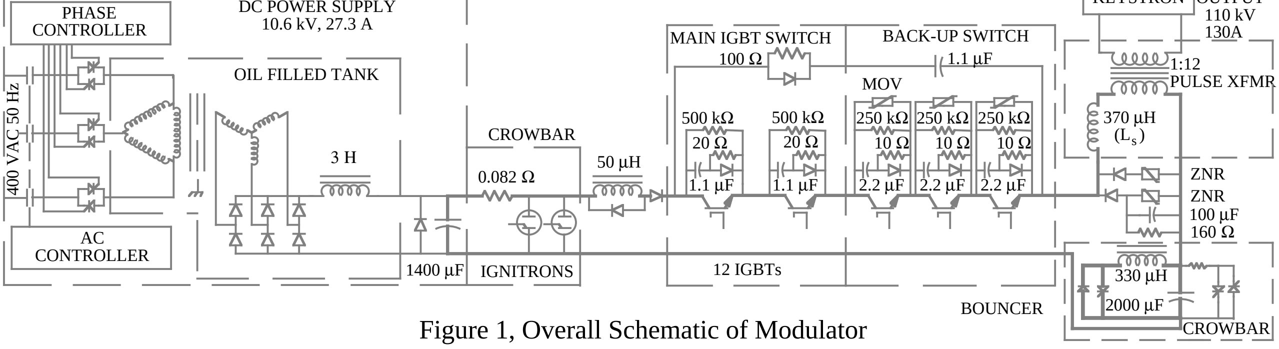

Figure 1, Overall Schematic of Modulator

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THE BACK-UP SWITCH

The function of the backup switch is to protect the klystron from damage in the event that the main switch fails to open during a klystron gun spark. It is not sufficient to merely trigger the capacitor bank crowbar, since the primary voltage must be driven negative to remove the energy stored in the pulse transformer's leakage inductance. This requires opening the switch. The backup switch is used in conjunction with the crowbar. MOVs protect the backup IGBTs from excessive voltage until the crowbar has removed the main capacitor bank voltage.

MECHANICAL CONSTRUCTION

One of the difficult problems with high voltage switches that open at full load is balancing the various concerns over voltage stress. The device and the high voltage interconnection stress must be kept low to maintain adequate safety margin for fault conditions. The interconnection inductance must be kept to a minimum to achieve low device stress, however the interconnection stress can be kept low by increasing inductance. This modulator uses strip-line connections to balance those concerns.

The complete path from the capacitor bank, through the switch to the transformer is built in the form of a strip-line, with the circuit return bus running alongside the high voltage connections The total stray inductance is kept to less than 2 μH. This approach is required to minimize stray inductance in the switch circuit because the energy stored in this inductance causes a voltage overshoot across the switch when it is opened.

Although the operating voltage level of the primary circuit is 10 kV, the IGBT switch will see higher stress levels during the course of normal running and faults due to the interconnection and other inductances. The maximum level that we expect the switch to see is 12.5 kV. Since we use the back-up IGBTs at one half voltage level in normal operation, there are 13.5 devices sharing this voltage, with 925 V per IGBT. If we add to this an expected 80 V imbalance due to device turn off time variations, we are then expecting a maximum stress of 1005 V on a 1600 V device. We feel comfortable with this margin.

The switch strip-line section must be corona free with 10 kV pulses between conductors. It was empirically determined and later confirmed by simulation (using OPERA 2D by Vector Fields) that increased corona free operation could be obtained by configuring the polycarbonate insulation as shown in Fig. 3. In the figure it can be seen that the insulation is layered. The center layer extends beyond the edge of the conductor by 1.5 inches in order to provide a long strike path to hold off the 10 kV potential difference between the two opposed conductors. By indenting the outer layers of polycarbonate as opposed to allowing all three layers to be the same width, we increased the corona free operating level from 6 kV_{rms} to 10 kV_{rms}.

With the input and output strip-line conductors at each IGBT in intimate proximity to each other it was necessary to insulate the opposed conductors with an insulation suitable for the 1600 Volt rating of each device. This was accomplished by coating the copper conductor with epoxy that was applied by a commercial powder coating process normally used in lieu of painting. The applied coating was built up until the thickness was .008" (0.2 mm) which has a DC voltage rating of 2 kV

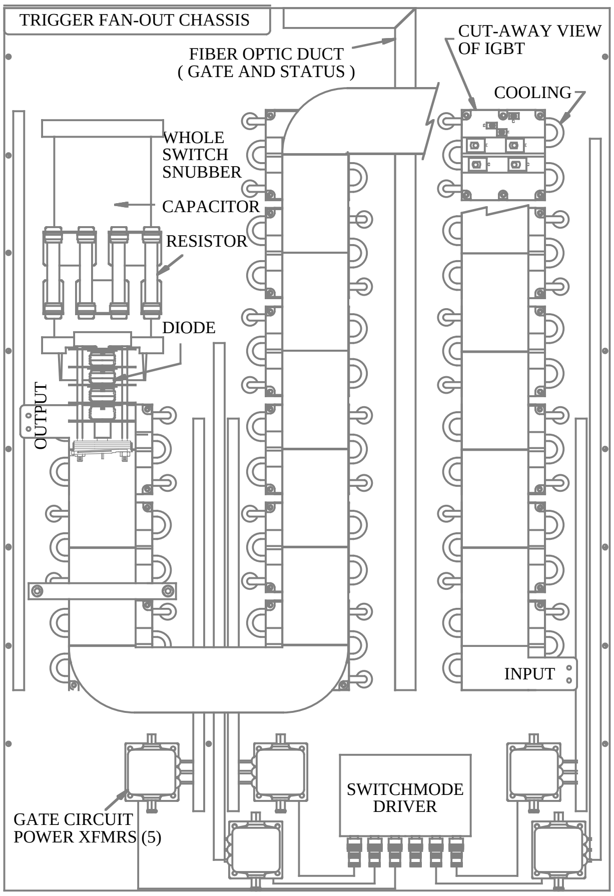

Figure 2
Front View of IGBT Switch

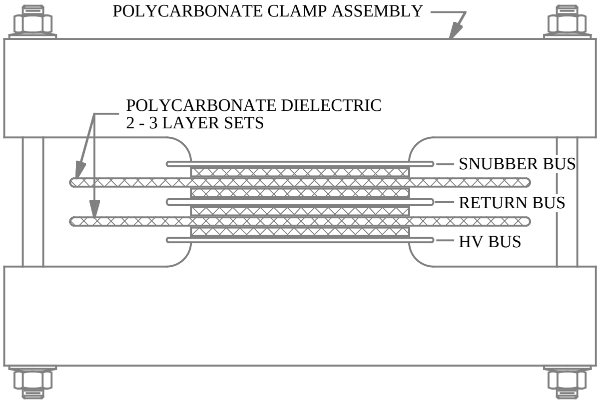

Figure 3
Bus Bar Cross Section

Each IGBT is mounted on a water cooled chill plate available from a commercial vendor. The fifteen chill plates are connected together in a series path for water flow. The water used is Low Conductivity Water with a resistivity greater than 1 Mohm-cm. The flow rate is approximately 1 gpm.

GATE CIRCUITS

To minimize gate driver inductance, each IGBT has its gate circuit mounted directly to its gate terminal. The driver circuit is developed around a commercially available IC, IXYS Corp. part # IXBD 414. The IC has a drive capability of approximately 3 A into a 10 nF load capacitance. Since this was not sufficient to drive the Eupec IGBT, a booster amplifier stage consisting of a complementary pair of bipolar transistors was added after the IC output. This combination is capable of providing 25A source and sink required for the 180 nF capacitance of our IGBT. The IC also incorporates a charge pump that generates the negative voltage needed by the IGBT in the OFF state. Additionally, the IC monitors the positive and negative power supplies for over and under voltage and the turn-on status of the IGBT. This status is reported to the control system via a fiber optic driver and cable for each IGBT in the series array.

The gate circuits require 2.5 W of 15 V power for their operation. Since the IGBTs are floating at up to 10 kV from ground it is necessary that power for the gate circuits be supplied via isolation transformers. These transformers were constructed to provide corona free operation to a level greater than 20 kV_{rms}. Each transformer has three independent secondaries to supply power to three separate gate circuits. Five transformers are required to provide the power for the 15 IGBTs. Primary excitation is generated by a switching converter running at 40 kHz that is capable of driving the five transformer primaries in parallel.

Coupling the gate signals to each IGBT is accomplished via fiber optic cables. A trigger fan-out chassis is used to branch the single trigger signal of the main switch to each of the respective IGBTs. A second trigger signal for the three IGBTs of the back-up switch is fanned out in a similar manner.

SNUBBER CIRCUITS

Each of the main IGBTs is protected by an RCD snubber network and a DC balancing resistor. The snubber circuit is mounted in a low inductance configuration to limit transients during the rapid device turn-off.

The three backup IGBTs snubber and balance circuits have half the impedance of the main switch circuits. These devices thus run at one half the voltage of the main switch devices. This low voltage allows us to protect the backup IGBTs with 480 V_{rms} MOVs, which are useful during failure modes.

Another RCD snubber circuit is installed in parallel with the entire switch to absorb the energy from the 2 µH tray circuit inductance and limit the switch-opening voltage overshoot to 2 kV. This snubber has a low inductance strip-line path through the switch. The snubber bus strip-line is shown in Figure 3.

STATUS

The first of the Tesla II modulators is almost complete and the second one is half finished. We have tested the IGBT switch to full voltage and current using a resistive load in place of the pulse transformer and klystron. Figure 4 shows the modulator output voltage and current with a 6 Ohm dummy load. Note that the pulse has a large slope because the bouncer circuit was not included for this test..

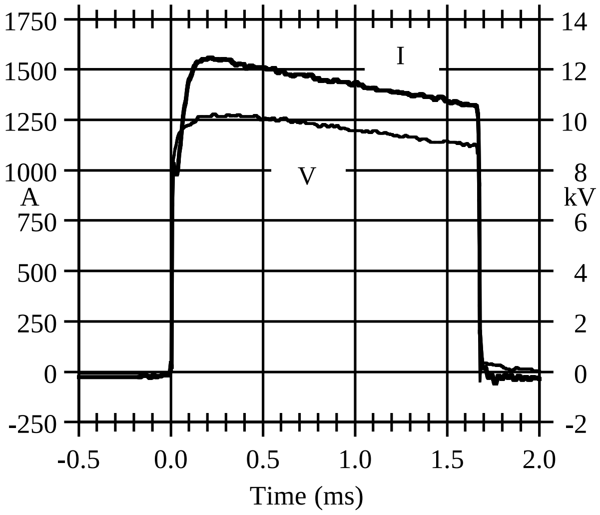

Figure 4
IGBT Test Output Voltage and Current

REFERENCES

[1] **A Long Pulse Modulator For Reduced Size And Cost**, H Pfeffer et. al., Fourth European Particle Accelerator Conference, London, 1994