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SOLID-STATE HIGH VOLTAGE MODULATOR WITH OUTPUT CONTROL UTILIZING SERIES-CONNECTED IGBTs

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GENERAL ATOMICS

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Solid-State High Voltage Modulator With Output Control Utilizing Series-Connected IGBTs

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ABSTRACT

The design of a solid-state high voltage modulator has been developed that uses series-connected insulated-gate bipolar transistors (IGBTs) to control the output voltage. Although having many potential applications, this high voltage modulator was designed to meet, at a minimum, the requirements of one of the power supplies required for depressed collector gyrotrons being used in electron cyclotron systems on devices performing experiments for fusion energy. Depending on the specific gyrotron, the output voltage is required to vary up to -80 kV with currents up to 100 A. In addition, square-wave modulation at frequencies up to 1 kHz is required. Four IGBTs are configured into a 2.4 kV IGBT module, and the number of IGBT modules that are connected in series is adjusted to meet the output voltage requirement. IGBT modules were successfully built and tested to verify the performance of the topology at 2.4 kV. The design of a -80 kV, 100 A modulator has been developed. The design is easily scalable for different applications and output voltages. A conceptual design was also developed for a -90 kV, 120 A power supply that has multiple intermediate taps to energize a multi-stage depressed collector gyrotron. This concept has twenty-four 4.5 kV, 120 A power supply modules that are connected in series. Each power supply module has three 2.4 kV IGBT modules, which provides sufficient voltage margin to support the additional voltage headroom needed for regulation and AC line fluctuations. If all of the power supply modules were equally sharing the total output voltage of -90 kV, then each module would be operating at -3.75 kV. The extra 18 kV of voltage margin adds the capability of reaching -90 kV with some of the modules putting out less than -3.75 kV. The description of the design of the IGBT modules and of the -80 kV, 100 A modulator will be presented. An overview of its adaptation to the concept for the power supply of the multi-stage depressed collector gyrotron will also be presented.

Index Terms — **high voltage, modulator, gyrotron, power supply**

1 INTRODUCTION

High power depressed collector microwave tubes (gyrotrons) require a regulating high voltage DC power supply to control the cathode potential. Depending on the gyrotron, a variable output voltage from 0 kV up to -80 kV and up to 100 A continuous current is required, with the capability to perform square-wave modulation of the voltage at up to 1 kHz.

General Atomics (GA) initially developed the design for a solid-state high voltage modulator using series-connected insulated-gate bipolar transistors (IGBTs) for the 95 kV, 20 A klystron power supplies of the Accelerator Production of Tritium project [1], Later this design was modified for a -70 kV, 80 A gyrotron power supply during a design study, and proposed for various rf sources [2]. During the development of two of these designs, bench tests were successfully performed to verify the topology and feasibility of switching IGBTs in series [2].

The electron cyclotron system on DIII-D has tetrode-based modulators in the existing power supplies. A planned upgrade of this system will have depressed collector gyrotrons, which have the capability to also modulate the rf output power using the body power supply. Because of this, solid-state high voltage power supplies have become an option for the cathode power supplies. To have a demonstrated product for interested potential customers and to provide an option for the future DIII-D upgrade, GA recently undertook to complete the design a 80 kV, 100 A solid-state modulator and to demonstrate its performance at a minimum of -50 kV, 50 A for up to 30 s into a water-cooled dummy load and to demonstrate modulation at up to 1 kHz [3].

The design of the solid-state modulator as a DIII-D gyrotron cathode body power supply is described below, as well as an adaptation of its design for a multi-stage depressed collector gyrotron.

2 THE DESIGN OF SOLID-STATE HIGH VOLTAGE MODULATOR

Figure 1 shows a simplified block diagram of the solid-state modulator. The series-connected IGBTs are switched at a fixed frequency by a pulse width modulation (PWM) regulator that adjusts the pulse width to control the voltage out of an inductor-capacitor filter network. A free-wheeling diode provides the current path when the IGBTs are switched off by the PWM. As a modulator for the gyrotrons at DIII-D, the solid-state modulator was designed for a maximum input voltage of -120 kVDC and an output of -80 kV and a maximum of 100 A.

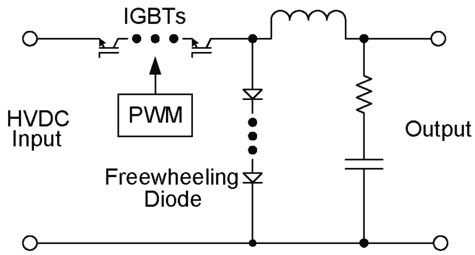

Figure 1: Simplified block diagram of solid-state modulator.

The series-connected IGBTs are grouped into modules, each having four 1200 V IGBTs mounted on a pair of water-cooled heat sinks as shown in the photograph of a fully assembled IGBT module in Figure 2. The IGBTs are operated at 600 V each, yielding 2400 V per module. Fifty modules are needed for the 120 kVDC input voltage. The snubber resistors for the IGBTs are also mounted on the heat sinks. The smaller snubber components for each IGBT are mounted on separate printed circuit cards (PCBs). The IGBT gate drive and fault monitoring circuitry is located between the IGBTs inside a shield box. IGBT module laminated bus bars were designed to reduce the inductance in the conductors that connect the IGBTs in series and to their snubber networks. They also provide the input and output connection points for the modules. The laminated bus bars passed hipot tests and the complete module passed the 2400 V pulse tests. Another laminated bus bar is used to connect the IGBT modules in series. This bus bar successfully passed its hipot test.

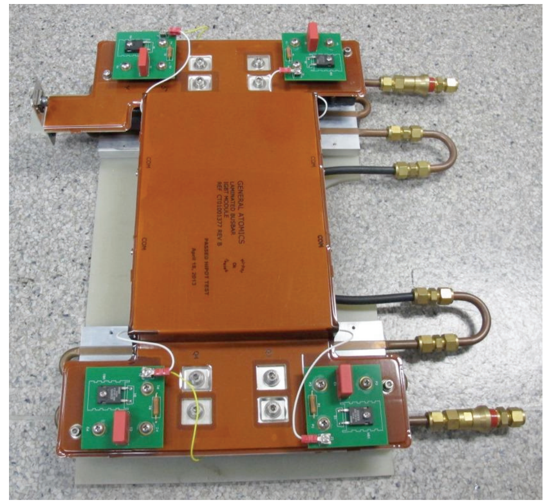

Figure 2: Photograph of a 2.4 kV IGBT module.

The layout of the solid-state modulator is shown in Figure 3. The IGBT modules are mounted in two rows within a frame of non-conducting material. The module in Figure 2 is for the bottom row. The HV input connects to the first IGBT module in the top row on the right in this view. An IGBT module interconnect bus bar connects the output of the module in the top row to the input of the module directly below it and routes the output of the lower module to the input of the next module in the top row. This sequence is continued along the two rows of IGBT modules and the output of the last IGBT module in the bottom row is connected to the inductor of the output filter.

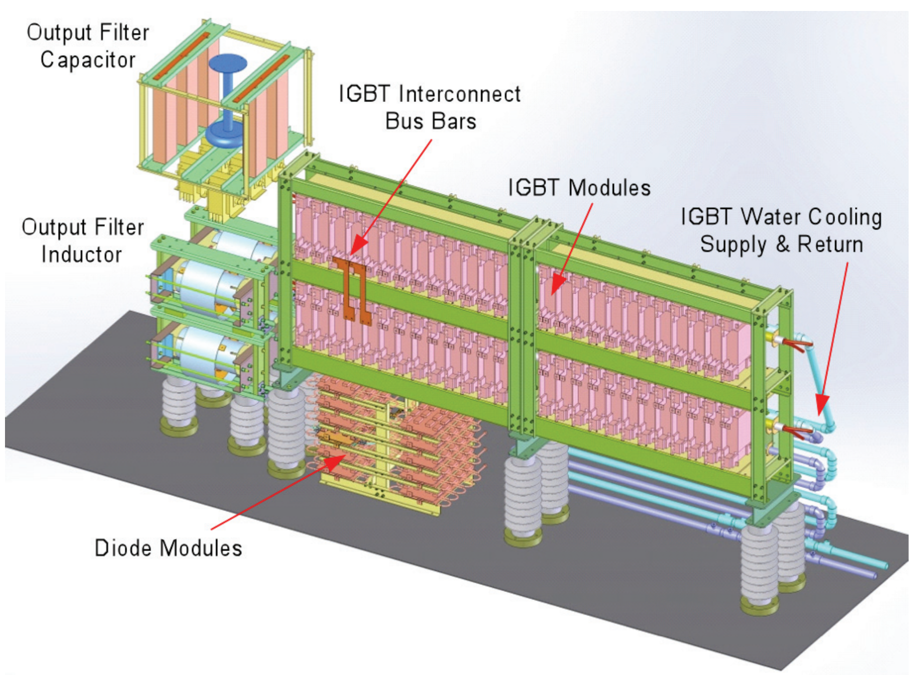

Figure 3: CAD layout of a solid-state modulator.

Two 15 mH inductors are connected in series to reduce the voltage isolation requirements for their design and construction. The filter capacitor is suspended from the ceiling directly above the inductor. Each of the five 0.01 μF capacitors has a 100 Ω current-limiting resistor in series with it.

The freewheeling diode is made up of 1200 V fast recovery diodes connected in series, which were also grouped into modules. Each diode module has 20 diodes that are mounted onto ten water-cooled heat sinks as shown the photograph in Figure 4. The snubber components for each diode are mounted onto small PCBs. A laminated bus bar was designed to connect the diodes in series and to their snubber networks, as well as providing the input and output connection points of the diode module. Diode module interconnect bus bars connect the diode modules in series. Both bus bars passed their hipot tests.

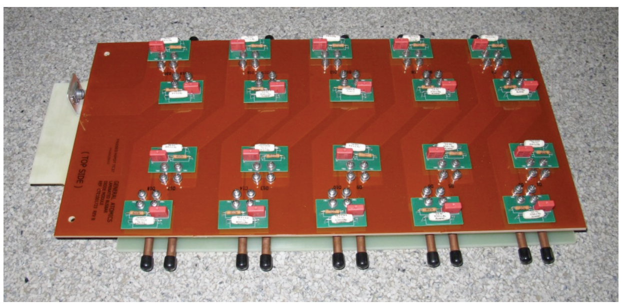

Figure 4: Photograph of an assembled diode module.

The eleven diode modules that are needed for the free-wheeling diode are in a frame of non-conducting material that is located below the IGBT modules near the filter inductor as shown in Figure 3. The lower terminal of the bottom-left diode module in this view is connected to the return bus. A diode module interconnect bus bar connects the top terminal of this module to the bottom terminal of the diode module directly across from it on the right and connects the top terminal of that module back to the bottom terminal of the next higher-up diode module on the left side. This sequence is continued up the two columns of diode modules and the top terminal of the highest module in the left column is connected to the junction of the filter inductor and the IGBT module.

Each IGBT module receives AC power from a toroidal isolation transformer. Plastic piping and tubing distributes the cooling water to the IGBT and diode modules. An IGBT module in the lower row and the one directly above it in the upper row are connected in series in the same cooling circuit. Each diode module has its own cooling circuit. The solid-state modulator is housed within a grounded metal enclosure with access doors on the front and back. The enclosure for the 120 kV modulator is approximately 20 ft long by 6.5 ft deep by almost 10 ft high. A lower voltage modulator would have fewer IGBT and diode modules and be shorter in length.

Simulations were performed using Simplorer® to show the anticipated performance of the design. Figure 5 shows the output voltage increasing to -80 kV and 100 A at turn-on and being maintained at that value. At 10 ms the output voltage is modulated at 50% duty cycle between -80 kV and -60 kV to simulate typical modulation of the cathode voltage for modulation of the rf output power of the gyrotron between full rf power and a very low level of rf power. At -80 kV the peak-to-peak ripple voltage in the simulation is approximately 280 V, less than 0.5% of the output. The modulation has a rise-time of about 100 μs.

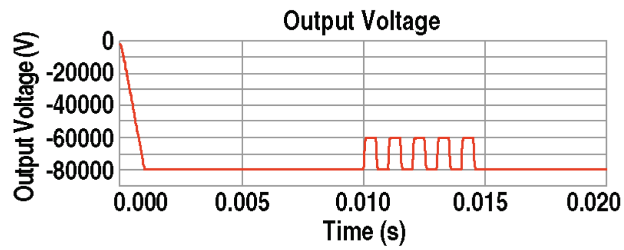

Figure 5. Simplorer® simulation result of output voltage at -80 kV with 1 kHz modulation from -80 kV to -60 kV.

3 ADAPTATION OF DESIGN FOR A MULTI-STAGE DEPRESSED COLLECTOR GYROTRON

Because of the modularity in the design of the solid-state modulator, it is easily scalable for different applications and output voltages by varying the number of IGBT modules. The following presents one such application in which a discrete power supply has three 2.4 kV IGBT modules.

Gyrotrons are continuing to be developed to produce higher power (>1 MW) for longer pulse lengths (approaching CW) and it is very desirable to increase the electrical efficiency of them. Single-stage depressed collector gyrotrons were developed and achieved electrical efficiencies as high as 50% compared to around 30% for gyrotrons without collector voltage depression. To achieve even higher efficiencies, multi-stage depressed collector gyrotrons are being considered. A cathode power supply for this gyrotron will need to have intermediate taps between ground and the full cathode potential to match the number of stages on the gyrotron, which could be as many as ten. The voltage applied to each stage needs to be adjustable while holding the total cathode voltage at a fixed value. The regulation of the voltage between taps can be less stringent than that for the full cathode potential. Such a power supply can consist of lower voltage power supply modules connected in series as shown in Figure 6. One or more of the power supply modules would be connected between adjacent taps. Multi-secondary transformers can provide the input AC power to the series-connected power supply modules.

A conceptual design was proposed for a -90 kV, 120 A power supply to energize a multi-stage depressed collector gyrotron. This concept has twenty-four 4.5 kV, 120 A power supply modules that are connected in series. Each power supply module has three 2.4 kV IGBT modules, which provides sufficient voltage margin to support the additional voltage headroom needed for regulation and AC line fluctuations. If all of the power supply modules were equally sharing the total output voltage of -90 kV, then each module would be operating at -3.75 kV. The extra 18 kV of voltage margin adds the capability of reaching -90 kV with some of the modules putting out less than -3.75 kV.

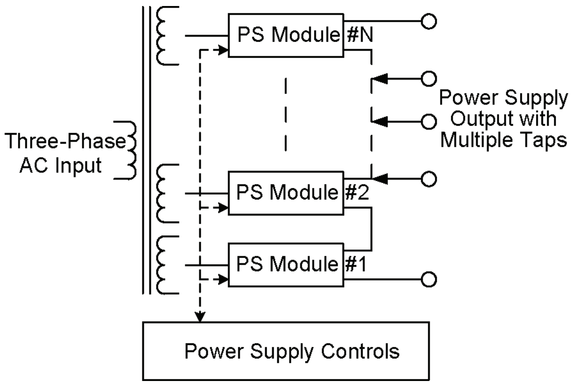

Figure 6. Simplified block diagram of a high voltage power supply consisting of discrete power supply modules connected in series.

In the proposed configuration, the PWMs in the 24 series-connected power supply modules switch at the same fixed frequency, but they are phase-shifted by thirty degrees relative to each other to yield a net 12-pulse ripple, thereby reducing the ripple in the total output voltage. The power supply control system distributes the twelve phase-shifted frequencies across the first set of twelve power supply modules connected in series and across the second set of modules in the same manner. Moreover, the PWM frequencies are distributed so that there is always 150° of phase shift between adjacent modules in the series string. Figure 7 shows a simulated waveform from Simplorer® of the voltage across 24 power supply modules at -90 kV with on/off modulation at 1 kHz with a rise-time of about 100 μs. Simulations also showed that at the full -90 kV output voltage, the peak-to-peak voltage ripple is 0.064% (less than 60V), reduced from the 2.16% ripple if the switching of the 24 power supply modules were not phase-shifted.

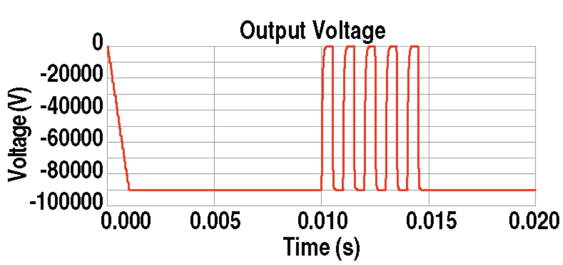

Figure 7. Simulated waveform of voltage across 24 power supply modules at -90 kV with on/off modulation at 1 kHz.

The taps to be connected to the stages of the multi-stage depressed collector gyrotron can be connected anywhere along the series-connected string of 24 power supply modules. The ripple in the voltage across adjacent taps will reduce as number of power supply modules between the adjacent taps increases, as shown in Figure 8. By having a phase-shift of 150° between adjacent power supply modules the percentage of ripple between adjacent taps reduces more quickly with increasing number of modules than with a 30° phase-shift.

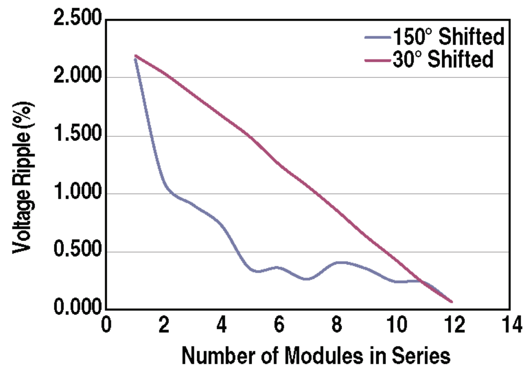

Figure 8. Plot of the percentage of ripple in the voltage between adjacent taps versus the number of power supply modules between the taps.

4 CONCLUSION

The design of a -80 kV, 100 A solid-state modulator has been developed to provide an option that could be incorporated into an upgrade on DIII-D instead of the building additional tetrode-based modulators. IGBT and diode modules have been fabricated and successfully bench-tested. The design was adapted to another application in which 24 power supply modules, each with three IGBT modules, are connected in series in a -90 kV, 120 A power supply for a multistage depressed collector gyrotron.

ACKNOWLEDGMENT

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