

Solid-State Modulator for Klystron /Gyrotron Conditioning, Testing, and Operation

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INTRODUCTION

The conditioning, test, and operation of high power microwave tubes, such as klystrons and gyrotrons, is a complex and costly process. Tubes must be conditioned over a range of increasing voltages, pulsewidths, pulse frequency, and input power levels to achieve reliable performance without damage. The process requires significant freedom of control of voltage, pulsewidth, and PRF, often at average power greater than 1 MW, peak powers greater than 20 MW, and voltages greater than 100 kV. Conventional modulator and power supply technologies capable of handling these high power levels are limited in their flexibility, and require significant operator knowledge, and take a long time to allow a tube to reach full performance. To address these issues, Diversified Technologies, Inc. (DTI) collaborated with Communication and Power Industries (CPI) in Palo Alto, CA under a Department of Energy grant to apply solid-state technology to the conditioning and testing processes. DTI combined two high power switches in a unique modulator/buck regulator configuration (Figure 8) to provide the required efficiency and control. The configuration was installed in CPI's MSR test set, where many of CPI's high power klystrons and gyrotrons are tested.

MODULATOR BASICS

Solid-state Modulator Principles

In its simplest configuration, solid-state technology provides a fast, high current series switch, or circuit breaker. These switches typically open and close in less than 100 – 500 ns, depending on their power rating.

When used as a Pulse Modulator, the opening and closing of the switch is controlled by a command signal at low voltage. The result is a stream of high power pulses into the load, each with rapid rise and fall times, and extremely consistent pulse-to-pulse characteristics. Because these solid-state modulators do not use resonant

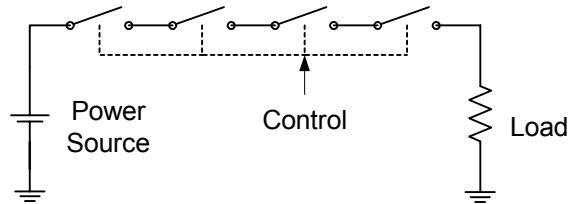


Figure 1. Solid-state modulator components. The switches are in series.

circuits, each pulse can be arbitrarily sized. This allows complete pulse width and separation flexibility - from 1 μ S to DC - on a pulse-to-pulse basis.

Figure 1 shows the basic design of a solid-state modulator using solid-state devices in series. This concept provides the flexibility of a modular design, with no inherent limit to voltage handling. Modules can be arranged in series for high voltage, in parallel for high current operation, or in other combinations to meet specific pulsed power

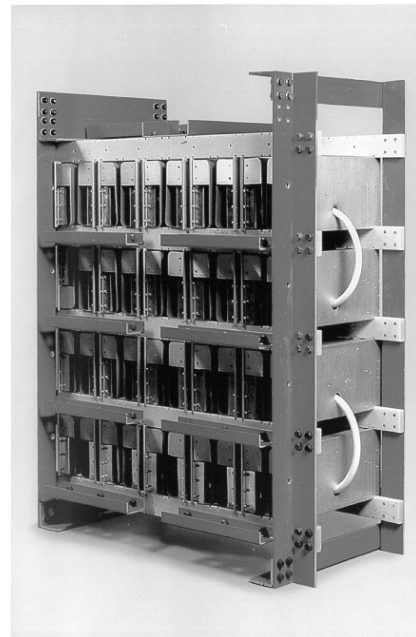


Figure 2. 140kV, 500A solid-state switch

requirements. However, it is necessary to ensure that the load is shared equally between devices so that no single device sees harmful or destructive voltages. DTI has developed and patented a highly synchronized, external gate drive which controls all modules simultaneously. The technology has been demonstrated at over 160 IGBTs in series, and up to six IGBTs in parallel.

HIGH POWER MODULATOR

The first solid-state switch was delivered to CPI in March 1999. This is a 140kV, 500A peak modulator capable of operation at pulsewidths from 1 microsecond to DC, and at PRFs of 10+ kHz (Figure 2.) This 70 MW peak power switch measures approximately 48" x 36" x 18", and is packaged with a storage capacitor, control circuitry, and voltage and current monitors into a complete modulator system (Figure 4). Each of the forty switch modules shown is capable of switching 500 A at approximately 3.5 kV.

This 140 kV modulator, shown in Figure 8 as the "fast series" switch", was installed in the MSR test set at CPI directly adjacent to the microwave



Figure 4: PowerMod™ 70 MW modulator

tube test cell. Figure 3 shows one sample pulse from initial testing of the modulator. The ringing on the voltage pulse is primarily instrumental, but the initial current peak is real. This current spike is due to the charging of the cable, socket, and load capacitance at the pulse inception. In this pulse, approximately 22 MW of pulsed power was

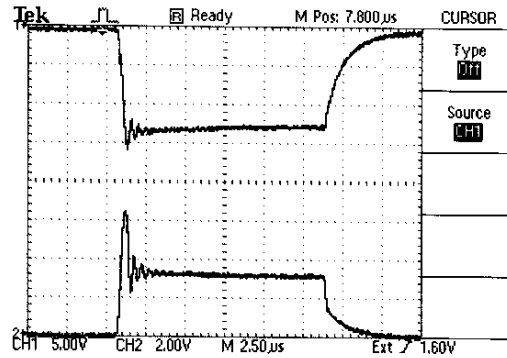


Figure 3: Test pulse (140 kV, 160 A, 13 μsec) of solid-state modulator. Upper trace is voltage at 63 kV/division. Lower trace is current at 100 A/division

delivered to the load from an 18 μF storage capacitor, with over 99% efficiency. The voltage drop across the semiconductor switch is a few hundred volts, including the insertion loss of the modulator and all auxiliary circuitry.

CROWBAR ELIMINATION

With a solid-state switch, load arcs are protected by sensing overcurrent of modulator output and terminating the pulse by simply opening the solid-state switch. This approach eliminates the need for a crowbar completely, and provides a higher level of protection to the tube when an arc occurs. Opening the series switch also eliminates the need to short the power supply – significantly reducing stress on these components, and allowing pulsing to resume immediately after the arc is cleared. Figure 6 describes how this occurs.

Prior to klystron testing, DTI successfully showed the modulator was capable of passing the "wire test" where a full voltage pulse into a 5 mil copper wire is interrupted without damage to the wire. Traditionally, this test is used to demonstrate that the arc energy deposited in the tube is less than 10 J.

Figure 5 (upper) shows the details of an overcurrent test into an intentional air-arc. In this case, an 80 kV pulse arcs over at about 60 kV (through a 1.5" gap). The current continues to rise, limited only by the internal inductance of the modulator, until the switch opens in response to the overcurrent sense. The trip threshold is set at 200 A, and the current is seen to drop about 700

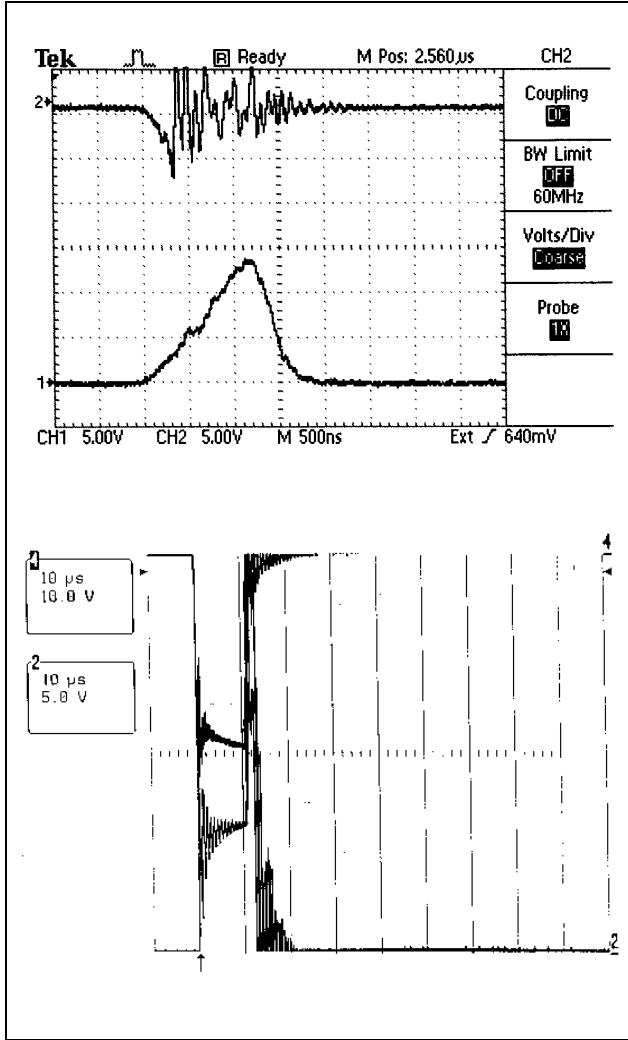


Figure 5. (Upper) Arc Test. Upper trace: voltage @ 50 kV/div. Lower trace: current @ 250 A/div. (Lower): 110 kV, 80 A pulse from MSR test set. Upper trace: cathode voltage @ 20 kV/div. Lower trace: cathode current @ 20 A/div.

ns. after this limit is reached. Note that the switch successfully opens (interrupts) a fault current of nearly 700 A.

The lower part of Figure 5 shows this current protection in action. This klystron under test was being pulsed at 110 kV. An arc occurred at 10 μ s into the pulse. The overcurrent condition was sensed and voltage removed by opening the series switch, extinguishing the arc. Tests at CPI verified that the tube is protected with less arc-deposited energy than CPI’s crowbar protection, at significantly less stress on key power supply components.

BUCK REGULATOR CONFIGURATION

The second large solid-state switch delivered to CPI was the “switching buck regulator” power supply. It uses a modulator similar to the one discussed earlier, but rated at 160 kV. This system was delivered to CPI in December, 1999. The total circuit, with both solid-state switches, is shown in Figure 8.

In the switching buck regulator configuration, HVAC power is rectified and filtered at a slightly higher DC voltage than required by the load (e.g., >110 kV for a 100 kV accelerator klystron). The solid-state switch is used to Pulse Width Modulate (PWM) this higher voltage to a diode stack and LC filter. The high speed, variable PWM serves as the voltage regulator for the system. Since the PWM frequency is much higher than the AC frequency (i.e., 5-25 kHz vs 60 Hz), the PWM also actively compensates for rectifier ripple. In the buck regulator configuration, this switch is Pulse Width Modulated at a frequency of 4 –10 kHz - resulting in a a DC-DC converter (buck regulator).

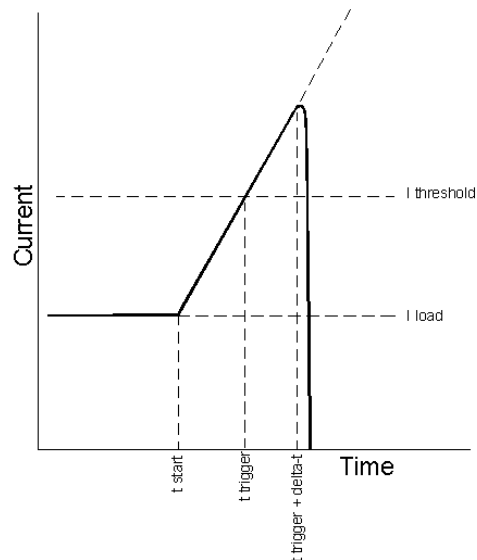


Figure 6. History of an arc. The nominal pulse current, I_{load} is exceeded when the load arcs. The current ramps up and quickly passes through a detection threshold, which is necessarily somewhat above the load current. The modulator takes some additional time after the current passes this threshold (about 700 ns) before the response loop completes and the solid-state switch opens. The ultimate peak current reached depends on the sensing threshold, the delay, the supply voltage, and the total series inductance.

The major differences between the modulator and the buck regulator configurations are the addition of the diode and inductor, and the Pulse Width Modulation (PWM) control of the switch itself. This switching buck regulator topology avoids the use of series pass tubes for regulation, with their high voltage drop and power dissipation. It also significantly increases the average power available at lower voltages, because the total power available from the transformer can be utilized at lower voltage.

This approach is much more compact and less expensive than either a full switching supply or large conventional transformer-rectifier supply. The inherent efficiency of these designs makes solid-state high voltage switching capability attractive for very high power systems, such as future accelerators where hundreds of megawatts CW of DC power are required.

Figure 7 shows the results of a buck regulator test. The data collected at CPI show over 95% efficiency at high power, with less than 40 V peak-peak ripple. This represents the highest voltage, highest power, switching power supply known to date.

The complete configuration of the buck regulator and modulator as installed at CPI is shown in the Figure 8 schematic. It provides a complete chain of solid-state control over voltage, pulsewidth, and pulse frequency. The speed of these solid-state devices provides a major improvement in arc protection and voltage regulation over conventional power supply and modulator technologies. The ability of the operator to control each of these parameters independently, and over a wide range, significantly reduces the

time required for conditioning and testing of high power microwave tubes. In operational systems, such as large, multi-klystron accelerators, this

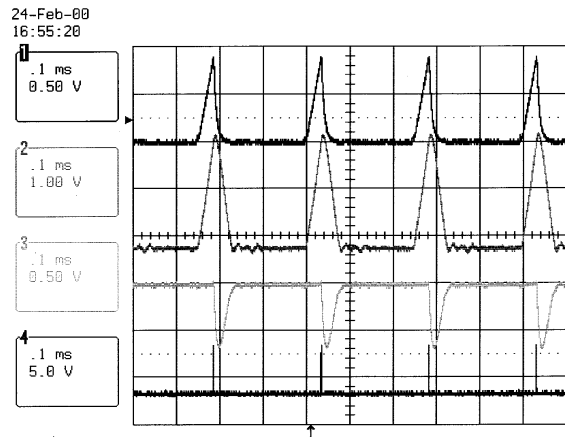


Figure 7. A high power run of the CPI buck regulator. The CW operating parameters were 117.3 kV and 81.9 A in, 61.34 kV and 15.7 A out – net 960 kW CW output. Overall efficiency was >92%, but the losses included > 30 kW in the CPI capacitor bank series resistors, for > 95% net efficiency of the buck regulator. The traces shown are (1) switch current at 50 A/div, (2) inductor current at 40 A/div, (3) diode current at ~50 A/div. The buck regulator is running at 4 kHz.

same reliability, efficiency, and flexibility can significantly reduce operating costs. The advent of practical, reliable, and affordable Solid-state high voltage switching opens a range of new tools for high power RF system design.

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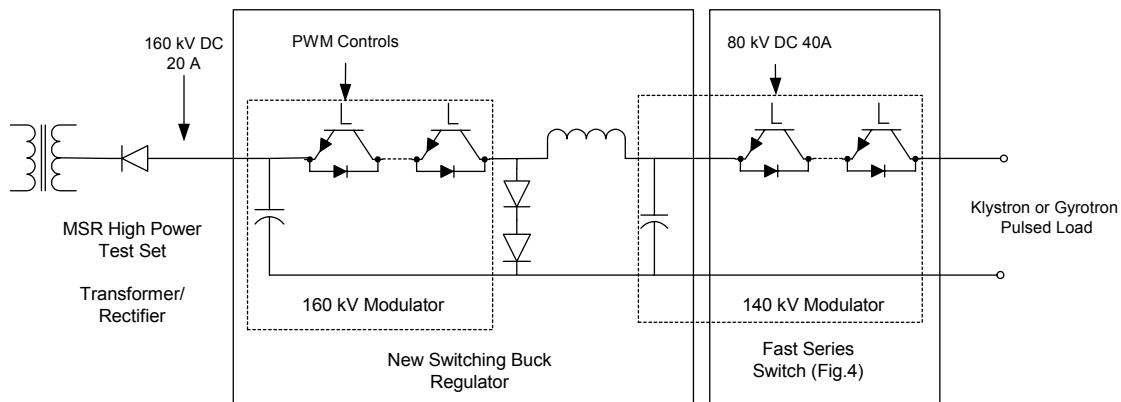


Figure 8. Modulator/Switching Buck Regulator Configuration