

# SOLID-STATE HIGH VOLTAGE PULSE MODULATORS FOR HIGH POWER MICROWAVE APPLICATIONS

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## Abstract

Diversified Technologies, Inc. (DTI) has successfully developed and demonstrated a highly efficient and reliable new approach to solid state switching that can be used in a wide range of high power microwave systems. Multiple switch modules can be combined in series and parallel to meet a wide range of power switching requirements. This paper describes how these switches have been used as replacements for vacuum switch tubes and incorporated into fully solid state modulators and power supplies for high power RF tube testing.

## 1 BACKGROUND – HIGH POWER, SOLID-STATE SWITCHING

The essential device in a pulsed power application is a pulse modulator, an electronic device used to provide high voltage, high current power bursts with great precision and accuracy. Ideally, a modulator acts as a simple switch between a high voltage power supply and its load, such as a klystron.

One conventional approach is to use a gridded vacuum switch tube, such as a triode or tetrode, as the series switch for a pulse modulator. This approach has three major drawbacks. First, the switch tube is current limiting which is detrimental to pulse rise-time. This forces a linear risetime slope due to the limited current available for charging the cable and load capacitance. Second, a very large voltage drop, which may be more than-20% of the total switched voltage ( $V_0$ ), exists across the tube. This means that the power supply must operate at a higher voltage than required. Additionally, this voltage drop, at high current, means a significant amount of power is being dissipated in the tube. Third, tubes, in general, arc, which reduces their lifetime and mandates complex conditioning, arc detection and crowbar protection systems.

A second conventional option for switching uses a Pulse Forming Network (PFN) and also has several drawbacks. For example, the requirement for variable pulsewidth at high PRFs is problematic for a thyatron/PFN pulser. In addition, the thyatron typically used to drive a PFN has a finite lifetime, and must be replaced at regular intervals. At high levels of operation, this can be a noticeable cost factor. Also, a thyatron can only serve as a closing switch, and cannot open during a pulse in the event of an arc. The damage thresholds of the target often require additional hardware (opening switch tube or crowbar) to limit arc damage. Finally, the DC

power supply required to drive a PFN must typically operate at about twice the voltage desired at the output unless a step up pulse transformer is used. Again, this increases the cost and complexity of the overall system.

Nonetheless, vacuum tubes have provided a nearly exclusive solution to the problem of high-voltage switching because no cost-effective alternatives were available. As future systems require higher voltage and power, the use of switch tubes becomes increasingly impractical due to their inherent voltage and current limitations.

Recently developed high voltage, high power, solid-state systems have demonstrated benefits such as the following:

- Efficiency  $\gg 90\%$
- Low component cost
- Very high average and pulse power densities ( $> 1000 \text{ MW/m}^3$  peak power)
- Voltage levels from 1 - 150kV
- Peak current levels from 0A to 5000A
- Pulse Repetition Frequencies (PRFs)  $>40 \text{ kHz}$  and above (up to 400 kHz demonstrated)
- Rise and fall times  $<100 \text{ ns}$
- Variable pulse lengths (1 $\mu\text{s}$  to DC)
- High Reliability

### 1.1 Solid State Modulator Principles

In its simplest configuration, solid-state technology provides a fast, high current series switch, or circuit breaker. State of the art switches typically open and close in less than 0.5  $\mu\text{s}$ .

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 solid state modulators do not use resonant circuits, each pulse can be arbitrarily sized. This allows complete pulse width and separation flexibility - from 1  $\mu$  to DC - on a pulse to pulse basis.

Historically, solid state devices have been low voltage devices. Recent advances in Insulated Gate Bipolar Transistors (IGBTs) have improved the voltage and current handling characteristics considerably. Today's typical devices have voltage ratings from 1200V-3300V and current ratings from 50A-1200A continuous. They also feature the very low drive current requirements of Field Effect Transistors (thus the Insulated Gate). This

eliminates the need for cascaded stages of bipolar drives required by the low betas of early high current bipolar circuit designs.

Figure 1 shows the basic design of a solid state series

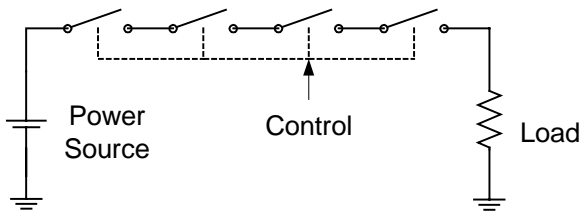


Figure 1: Solid state modulator components .The switches are in series.

modulator. This concept provides the flexibility of a modular design, with no inherent limit to voltage handling. However, it also necessitates the formidable task of ensuring that the load is shared equally between devices so that no single device sees harmful or

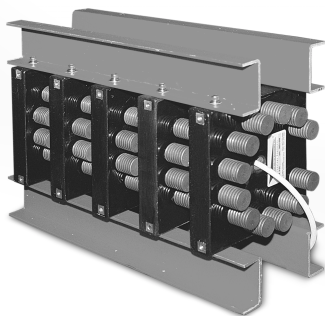


Figure 2: 45kV, 30A switch constructed of five 9kV, 30 modules.

destructive voltages. The gate drives must be highly synchronized to accomplish this. Systems having high voltage and/or high current requirements can be constructed by stacking these switch modules in various series and parallel configurations. An example is shown in Figure 2. DTI has developed and patented the technology to achieve this synchronization, and has

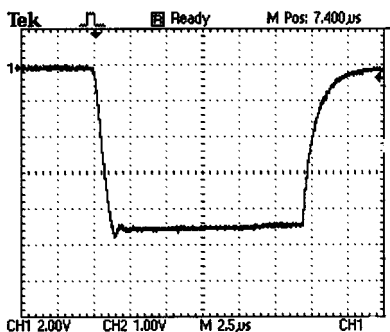


Figure 3: Solid State Modulator Pulse at 80 kV, 90A (Source: Diversified Technologies).

shipped commercial units with up to 160 IGBTs in series, and up to six IGBTs in parallel.

Achieving, as closely as possible, an ideal pulse is critical to the performance of a number of pulsed power applications, and is, therefore, a critical objective of high pulsed power system design. An "ideal pulse" has instantaneous rise and fall time, and a flat top, independent of load current and repetition rate. Very fast rise and fall times minimize the energy provided at voltages other than  $V_0$ .

Figure 3 shows the nearly ideal square voltage and current traces from a DTI solid state commercial modulator. The rise time of this pulse is less than  $1\mu\text{s}$  into a resistive load. The flat top of the pulse results from appropriate sizing of the storage capacitor, since the closed switch acts as a very low impedance connection directly between the capacitor and the load. The turn-off time of the switch is essentially equivalent to the turn-on time - the fall time shown is dominated by the discharge of load and cable capacitance through a pulldown resistor. Similarly, the slight overshoot is a function of inductance in the high voltage circuit rather than the switch performance.

Finally, the switch has a voltage drop of less than  $3\text{V/kV}$  ( $< 0.3\%$ ) when closed, and a leakage current  $< 1\text{mA}$  when open. The switch is very nearly "ideal" for most high power applications.

## 2 HIGH POWER TUBE TESTING

A second new application of high power, solid state switching technology is the testing of high power microwave tubes such as those used in accelerators.

Under a recently completed DOE Phase II contract, DTI developed and installed the world's highest power, solid state, high voltage modulator at Communications and Power Industries (CPI) in Palo Alto, California (Figure 4). CPI is using the modulator for testing and conditioning high power klystrons, such as the prototype for the Spallation Neutron Source (SNS) program. The modulator is rated at 140 kV and 500 A peak, and designed to pulse at up to 10 kHz. This product uses commercial high voltage IGBTs with DTI's patented gate drive protection and circuits.

The 140 kV modulator shown in Figure 4 and in Figure 6 as the fast series switch, has been installed in the MSR test set at CPI. An improved power delivery system that utilizes a modulator similar to a DC-DC converter (buck regulator) has also been installed (Figure 6). In this configuration, the full power of the existing DC supply can be provided at lower voltages and proportionally higher currents at high efficiency. The modulator at the heart of the buck regulator is identical to the 140 kV switch, with the further addition of more switch units to provide extra voltage handling capability. Pulse Width Modulation (PWM) at 4kHz provides excellent control regulation of the operating voltage. The inductor and



Figure 4: PowerMod™ HVPM 140-500 modulator with controls. (approximately 4' x 5' x 6')

capacitor at the output of the buck regulator provide filtering of the DC voltage.

In operation, loads are protected from arcs by sensing of modulator output overcurrent and termination

Results show that the buck regulator efficiency is dominated by the resistive losses, primarily in the inductor. At DTI, moderate current tests (~ 10A CW) have yielded efficiencies over 99%. The 160kV buck regulator has a more lossy (solid copper) inductor, and recently operated at 92-93% efficiency in CW 1MW operation.

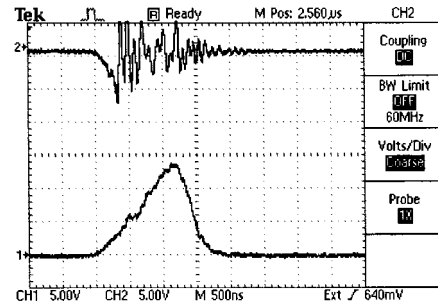


Figure 5: Arc Test. Upper Trace Voltage @ 50 kV/div. Lower Trace: Current @ 250 A/div.

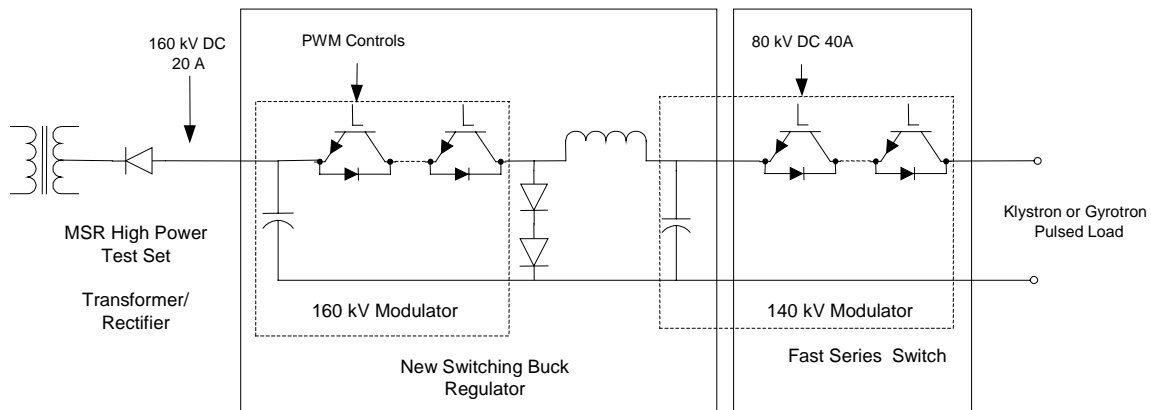


Figure 6: Modulator/Switching Buck Regulator configuration.

of the pulse. After overcurrent is sensed, the switches open in approximately 700 nsec. Prior to klystron testing, DTI successfully showed the modulator was capable of passing the “wire test” where a full voltage pulse into a 40 gauge copper wire is interrupted without damage to the wire/

Figure 5 shows this current protection in action. The tube is pulsed at 110 kV, and a tube arc occurs at 10 µs into the pulse. The overcurrent condition is sensed and voltage is removed, extinguishing the arc. Tests at CPI show that the tube is protected with less arc-deposited energy than CPI’s crowbar protection, at significantly less stress on key power supply components. Since the modulator simply opens in the event of an arc, pulsing can resume immediately after the arc clears.

### 3 CONCLUSIONS

- Solid state pulsed power is both feasible and practical at high voltage (over 150kV) and high power (tens of MW pulsed).
- Solid state modulators provide nearly ideal high power pulses, with sub-microsecond rise and fall times, high efficiency and very low droop
- As a fast opening switch, solid state modulators eliminate the need for crowbar systems, and provide much higher levels of protection than crowbar systems.
- A solid state modulator, with minimal modifications, can provide a very high efficiency DC-DC transformer, providing full power over a wide range of output voltages.