

# DTI Technical Brief

## Solid-State Pulsed Power Systems

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Presented at the 1998 Twenty Third International Power Modulator Symposium, Rancho Mirage, CA June 1998

### ABSTRACT

High energy physics, particle accelerators, and commercial semiconductor and metal treatment processes require reliable, high power, variable pulsewidth, flat top, high voltage pulses at high power. New processes for food sterilization, waste treatment, pollution control, and medical diagnostics and treatment are also being developed which require high power, high voltage pulsed power.

The technology needed to enable solid state high voltage, high power systems is now available. It has been demonstrated that solid state electronics can bring strong benefits to high voltage, high power systems design including:

- Efficiency > 90%
- Low component cost
- Very high average and pulse power densities (> 10 MW/m<sup>3</sup> peak power)
- Multimegawatt-level average power
- Voltage levels from 1 - 150 kV
- Average current levels from 10 A to 1200 A
- Pulse Repetition Frequencies (PRFs) of 30 kHz and above (up to 400 kHz demonstrated)
- Rise and fall times as below 250 ns
- Variable pulse lengths (1 $\mu$ S to DC)
- High Reliability

### TECHNOLOGICAL BACKGROUND

#### Modulator Alternatives

Ideally, a modulator acts as a simple switch between a high voltage power supply and its load (such as a klystron). The desired properties of such an ideal switch would be infinite voltage holdoff, infinite off-resistance, zero on-resistance, and full immunity to transients and voltage reversals.

Figure 1 shows an "ideal pulse" having instantaneous rise and fall time, and a flat top, independent of load

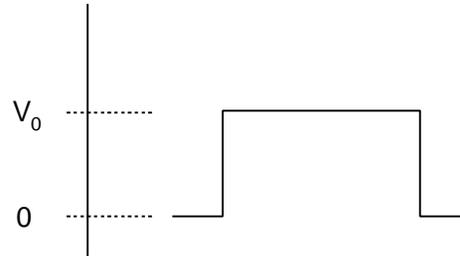


Figure 1: Ideal Pulse

current and repetition rate.

Achieving, as closely as possible, this ideal pulse is critical to the performance of a number of pulsed power applications. For ion implantation applications, for example, it is critical to minimize the voltage droop and pulse to pulse voltage variation to achieve uniform processing. This requires very fast rise and fall times to minimize the energy provided at voltages other than  $V_0$ . It also requires a very 'flat-top' for the pulse, with no ripple or droop. In a radar transmitter, the rise and fall times must be within the amplifiers' operating parameters, but the flat top is very critical to parameters such as phase noise. Generating pulses, which most closely approach the ideal pulse waveform, is, therefore, often a critical objective of high pulsed power system design.

Historically, vacuum switch tubes or thyratrons, alone, or in combination with Pulse Forming Networks (PFNs) and pulse transformers, have been used for this purpose. The non-ideal behavior of these conventional switches includes a large effective voltage drop, limited current capability and speed, high maintenance, and complex driving and protection circuitry. Nevertheless, they have provided a nearly exclusive solution to the problem of high-voltage switching until recently because no cost-effective alternatives were available.

As future system requirements extend to higher voltage and power, the use of switch tubes becomes increasingly impractical due to the inherent voltage and current limits of these devices.

### Solid State Modulator Principles

Solid state devices are, in general, low voltage devices. Recent advances in Insulated Gate Bipolar Transistors (IGBTs) have improved the voltage and current handling characteristics considerably. 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.

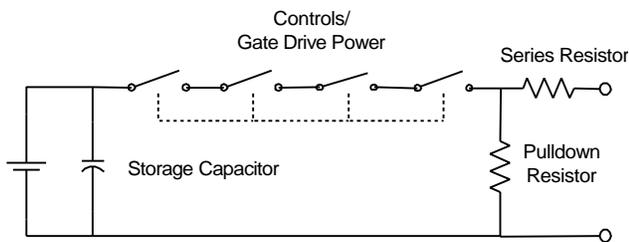


Figure 2: *Solid State Modulator Components*

To use IGBTs for high voltage switching, many devices must be cascaded in series. 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 destructive voltages. The gate drives must be highly synchronized to accomplish this. DTI has developed and patented the technology to achieve this synchronization, which has been demonstrated at up to 160 IGBTs in series, and up to six IGBTs in parallel.

Figure 2 and Figure 3 show the basic components of a solid state series modulator, including the storage capacitor and sixteen series connected IGBTs. The modulator in Figure 3 is capable of providing peak pulses of 40 MW (20 kV, 2000 A) at up to 1 kHz.

A commercial implementation of this technology is DTI's PowerMod™ HVPM20-150 shown in Figure 4. This device provides 20 kV, 150 A (3 MW) peak pulses in a single 19" rack-mountable unit. It was selected by R&D Magazine as "One of the 100 Most

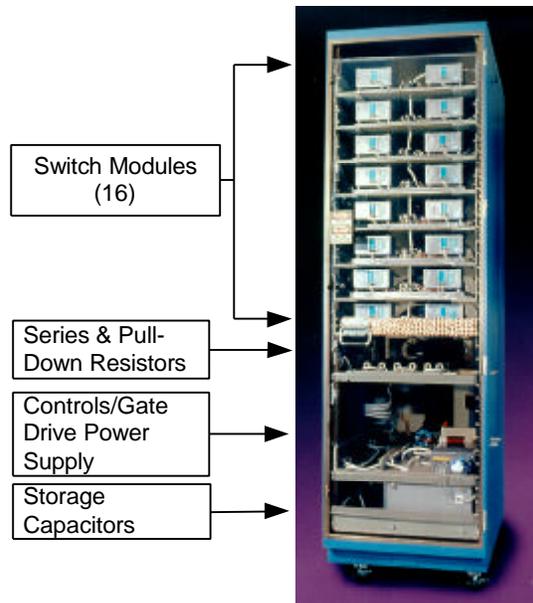


Figure 3: *High Voltage, High Power, Solid State Modulator Design (Source: Diversified)*



Figure 4: *20kV, 150A, 3MW Modulator (Source: Diversified Technologies, Inc.)*

Significant Technological New Products of 1997". It can nominally pulse at up to 30 kHz, limited only by the air cooling of the unit. In burst mode, however, this same unit can pulse at up to 400 kHz for short periods.

## NEARLY IDEAL SOLID STATE PULSES

Figure 5 shows the nearly ideal square voltage and current traces from the HVPM 20-150 solid state switch. Figure 6 shows a pulse from a higher power solid state 100 kV, 150A modulator such as the one shown in Figure 7.

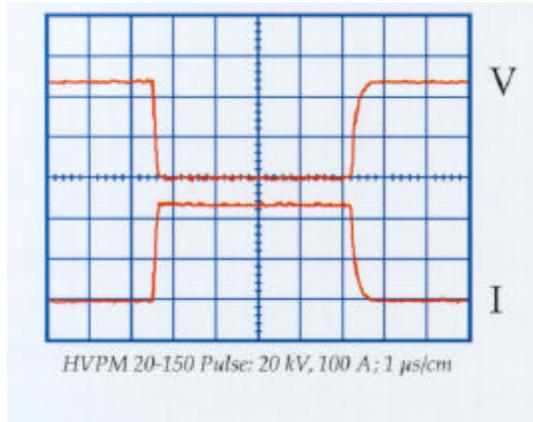


Figure 5: 20kV, 100A Solid State Pulse  
(1  $\mu\text{s}/\text{cm}$ )  
(Source: Diversified Technologies, Inc.)

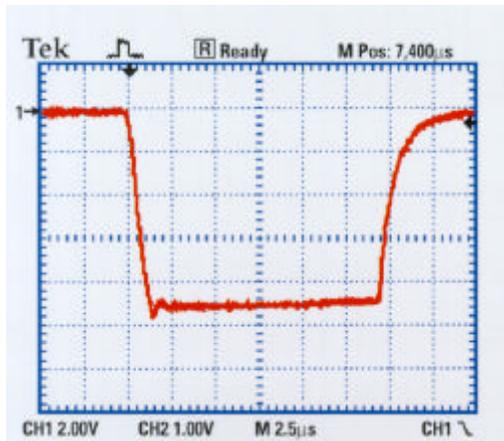


Figure 6: Solid State Modulator Pulse at 80kV,  
90A (Source: Diversified Technologies, Inc.)

In each case the rise times of these pulses are less than  $1\mu\text{S}$  into resistive loads. The flat top of the

pulses results from appropriate sizing of the storage capacitor, since the closed switch acts as a very low



Figure 7: 100kV, 150A Solid State  
Modulator. Dimensions are 3' x 4' x 5'.  
(Source: Diversified Technologies, Inc.)

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 the pulldown resistor shown in Figure 2. Similarly, the slight overshoot seen in Figure 6 is a function of inductance in the high power (7.2 MW) load, rather than the switch performance.

Finally, these switches have a voltage drop of less than  $3\text{V}/\text{kV}$  ( $< 0.3\%$ ) when closed, and a leakage current  $< 1\text{mA}$  when open. These switches are very nearly “ideal” for most high power applications.

## TECHNICAL APPLICATIONS

### *Simple Switch / Pulse Modulator*

In its simplest configuration, this solid state technology provides a very large, very fast series switch, or circuit breaker (Figure 1). Since these switches are both opening and closing switches, power can be completely removed from the load when the switch is ‘off’, or open.

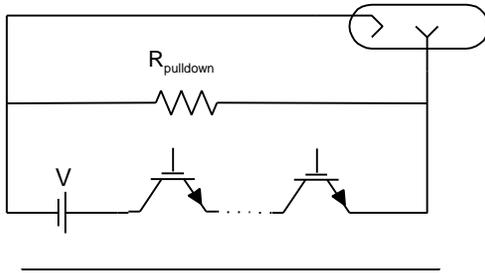


Figure 9: Mod Anode Modulator

State of the art switches typically open and close in less than 0.5  $\mu$ S. This capability allows **solid state switches to replace ‘crowbars’ in vacuum tube applications.** (See Figure 8). Should either instantaneous or average current through the switch rise above pre-set limits, the modulator simply opens, removing power from the load. **The delay from sensing of an over-current condition, such as an arc, to the opening of the switch has been measured at under 0.6  $\mu$ S.** In addition to this fast response, the ‘opening’ of the solid state switch does not shut down power supply operation, as with most conventional crowbars.

*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. Since the switch design and construction is identical in both a pulsed application and as a series switch, the same solid state modulator can be used simultaneously as a pulse modulator and as a fast fault protection disconnect system - significantly simplifying the overall system design.*

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  $\mu$ S to DC - on a pulse to pulse basis, which opens a host of new operating regimes to high voltage systems.**

In 1997, two prototype 20kV 100A mod-anode pulsers of the design shown in Figure 9 were supplied to MIT Bates Laboratory for use in their linear accelerator. The large unit shown on the left in Figure 10A below was replaced by a prototype solid state system, which fit completely in the small space beneath the tubes as shown in Figure 10B. Based on extensive testing of these prototypes, MIT is installing twelve additional solid state DTI modulators throughout the accelerator.

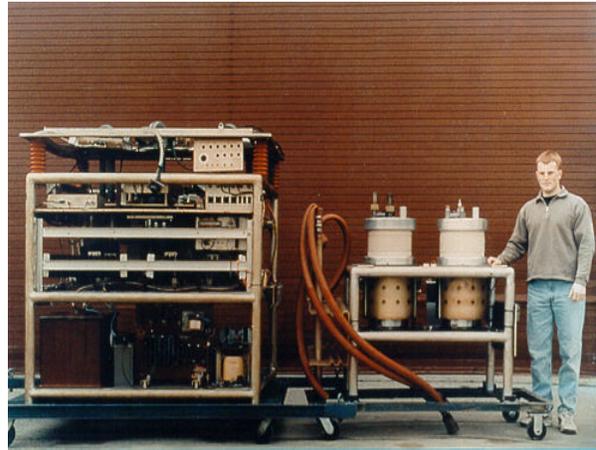


Figure 10A: Before

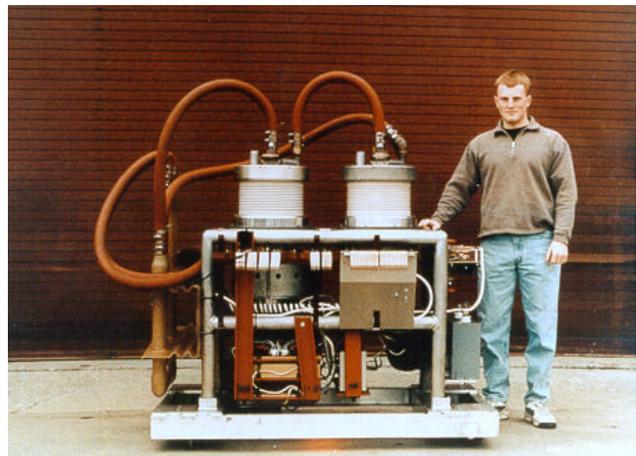


Figure 10B: After

### *Megawatt Switching Power Supply*

Solid state modulators can act as ideal ‘switchers’ for high voltage, Megawatt-level DC power supplies. Traditionally, this switching must occur at much lower voltages than the high voltage DC output - requiring a step-down transformer prior to switching, and a step-up transformer before rectification at high voltage. This is an inefficient process, requiring very large currents at the switching voltage. In a typical Megawatt scale power supply, use of rectified 60 Hz AC power also leads to very high ripple on the DC output, which requires significant filtering.

The high voltage switching capability of solid state modulators allows this switching to occur at higher

voltages (20 - 200 kV), approximating the required DC voltage, and eliminating the large, expensive, and inefficient step-down and step-up transformers. **This approach provides a very high efficiency, high voltage DC power supply.**

In Figure 11, AC 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

enable new applications, such as Megawatt switching power supplies, and fast-opening tube protection circuits. The flexibility, efficiency, and nearly ideal switch performance available from solid state technology is spurring a wave of innovative design for future high power systems.

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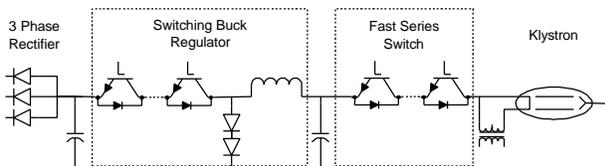


Figure 11: Switching Buck Regulator Schematic  
(With Additional Fast Series Switch)

compensates for rectifier ripple. This approach is much smaller and less expensive than either a full switching supply or large conventional transformer-rectifier supply. A 100kV, 40A (4MW) DC supply would be approximately the size of the modulator shown in Figure 7. A second series switch can still be used at the output for tube protection and/or pulsed operation. 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.

## CONCLUSIONS

Solid State Switches/Modulators capable of operating at high voltage and high power are in use as high voltage pulsers for demanding applications in semiconductor manufacturing, aerospace, flat panel display technologies, and Plasma Immersion Ion Implantation of automotive components. These systems extend from 300 kW to 40 MW in peak power.

Using this solid state technology, most of the limitations of conventional high voltage switching (inefficiency, limited lifetime, pulse flexibility, etc.) are eliminated. Solid state systems can replace switch tubes / PFNs, etc., in existing applications. They also

  
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