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Solid-State Modulators for Directed Energy Applications

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Directed energy/impulse power (DE/IP) systems offer solutions for a wide range of emerging applications including sensors, electronic countermeasures, clearing of improvised explosive devices and mines, and weapons. However, it is becoming clear that the conventional electronic breakdown switches currently used in DE/IP systems are not well suited for the demands of the future because of their limited reliability and adaptability. Recent developments at Diversified Technologies, Inc. (DTI), in solid-state switch technology are yielding significantly increased pulse energies and speeds. Solid-state switches now approach the performance required for DE/IP applications and offer the added benefits of inherent reliability, pulse flexibility, and operation at high pulse frequencies. In this paper, DTI will provide an overview of these developments and describe how system designers can apply them to new DE/IP designs.

KEYWORDS: Modulator, Pulse power, Solid state

1. Introduction

Directed energy and impulse power (DE/IP) systems have been the subjects of significant research and development over the past 50 years. They have been used chiefly in support roles such as assessing susceptibility to electromagnetic interference, simulating nuclear blast effects, and related research and development tasks. However, new mainstream applications for DE/IP systems are rapidly emerging in sensors, clearing of improvised explosive devices and mines, electronic countermeasures, and a range of other operational systems. To address these new challenges, the reliability and flexibility of the breakdown switches used in present-day DE/IP systems must be improved.

The work of Diversified Technologies, Inc. (DTI), in solid-state switching and power conversion holds great promise for spurring these improvements. The company pioneered the application of low-voltage, solid-state devices in high-speed, high-voltage switches requiring high peak power (pulsed) and high average power (continuous wave). DTI's systems combine multiple, lower voltage solid-state devices [such as insulated gate bipolar transistors (IGBTs)] in series and/or parallel, into a single switch that can switch power at voltages and currents orders of magnitude higher than can be switched by the lower voltage devices. As a result, the need for large transformers, mechanical switches, or vacuum tubes in the power conversion system is eliminated. Power conversion strategies that were once available only at low power and voltages are now applicable to high-power, high-voltage DE systems.

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Solid-state switches, operating at very high pulse frequencies, are inherently reliable, pulse stable, and pulse agile. As their underlying device technology continues to improve, solid-state switches are increasingly capable of delivering the performance necessary for DE/IP applications, with the reliability needed for operational systems.

2. Candidate Architectures

Much of DTI's work has been motivated by the high power requirements of large particle accelerators and fusion systems. The company has fielded power supplies capable of delivering more than 3-MW average power at more than 150 kV, pulsed systems capable of providing more than 250-MW peak at 500 kV, and hundreds of systems operating at lower voltage and power levels. Although the solid-state switching devices are often larger than comparable discharge/breakdown switches, solid-state *systems* typically have overall power densities up to an order of magnitude higher than conventional approaches, with very high reliability.

In this section, we will discuss three different architectures: DTI's hard switch modulator, hybrid modulator, and Marx bank modulator, all of which can satisfy DE/IP power requirements.

2.1. Hard switch

The hard switch is the simplest modulator design, consisting of only a capacitor and a full-voltage switch, shown in Fig. 1. A hard switch is analogous to a light switch. The switch simply turns on to apply voltage to the load and off to remove it. The capacitor determines the voltage applied, and this voltage decreases as the capacitor discharges. In this architecture, the solid-state switch must be rated to handle the full voltage and current of the load (including fault currents). Typically, a dc power supply is used to charge the capacitor to a defined initial voltage between pulses. In many applications, only a fraction of the capacitor energy is used in each pulse to maintain the pulse voltage: the capacitor serves essentially as a filter between the supply and the load. For long pulses, when the capacitor would be significantly discharged during each pulse, a "bouncer," shown in Fig. 2, can be used to maintain pulse flatness at significantly smaller capacitor sizes.[2]

2.2. Hybrid modulator

Figure 3 illustrates a hybrid modulator architecture in which a solid-state "hard" switch and a pulse transformer are combined. There are a number of benefits to this design,

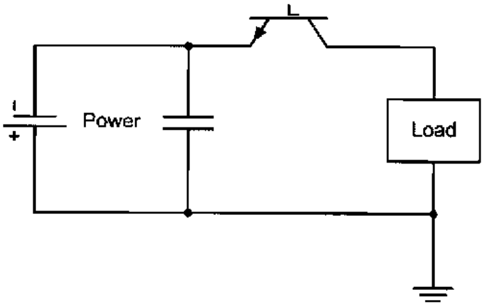

Fig. 1. Simplified schematic of a hard switch.

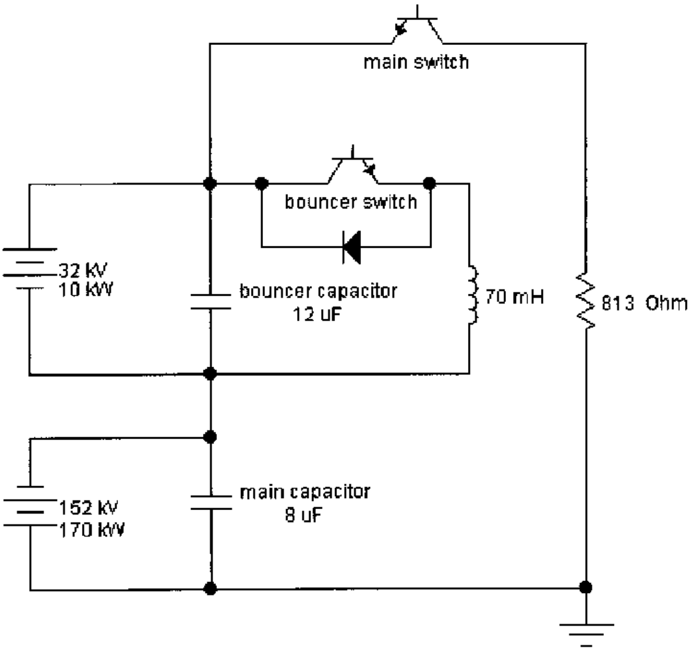

Fig. 2. Hard-switch circuit, including bouncer to give flat pulse.

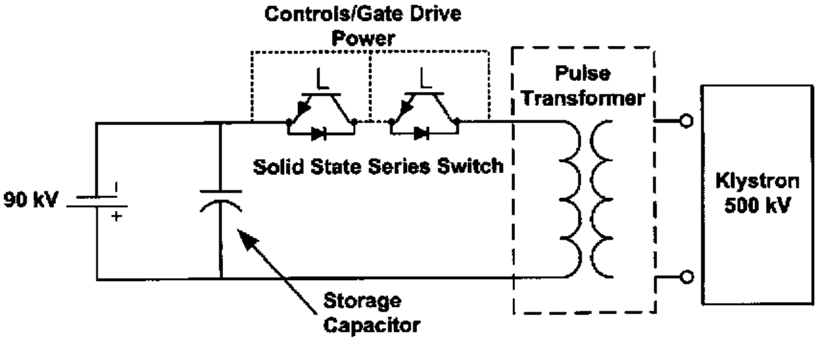

Fig. 3. Hybrid modulator architecture.

primarily that the engineering of the hard switch is simplified by operation at the lower voltage of the primary windings. At the limit of this design, the primary voltage is within the capability of a single device. Unfortunately, since the peak pulse power for a given application does not change, the primary current increases as the primary voltage decreases. When this outstrips the capability of a single device, multiple devices must be configured in parallel. While possible, this has significant detrimental effects on reliability, since the failure of a single device renders the entire system inoperable. Other designs have used separate primary windings to overcome this limitation, at the cost of increased transformer complexity.

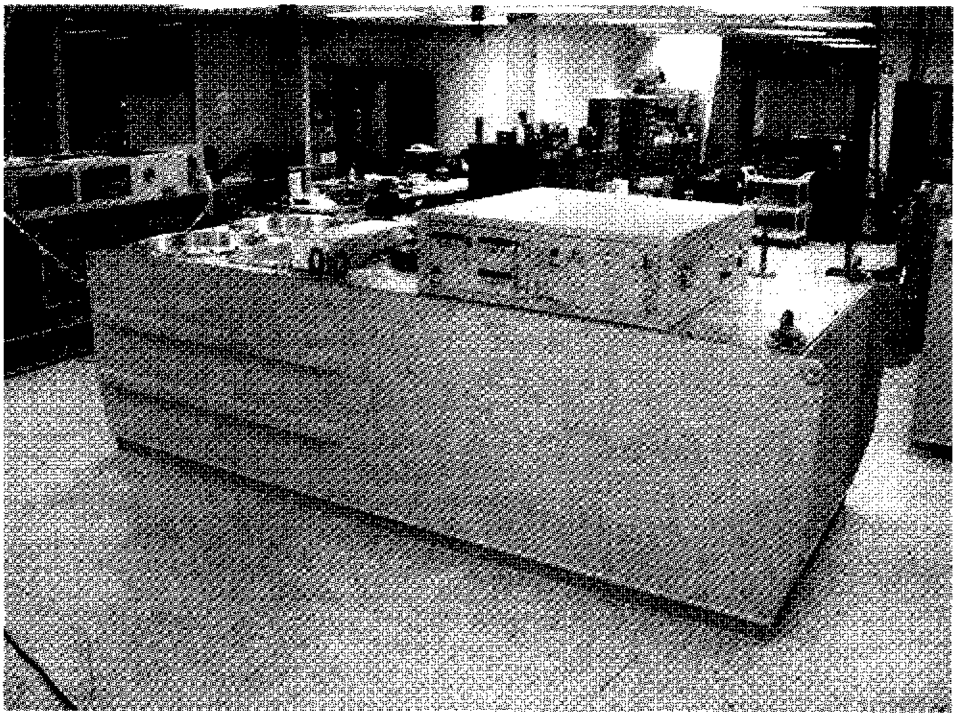

Fig. 4. Hybrid modulator in tank at DTI. Controls are in housing on top of tank.

Under a U.S. Department of Energy (DOE) Phase II Small Business Innovation Research program, DTI built and delivered a hybrid modulator[†] to the Stanford Linear Accelerator Center (SLAC) for the purpose of driving two Next Linear Collider (NLC)[‡]-class klystrons. The performance requirements of this system were demanding: pulses of 500 kV into a klystron load at 530 A, fast risetime ($<1\ \mu$s), arc protection, $\pm 3\%$ flattop, and low cost. The complete system, shown in Fig. 4, includes a 150-kW, 90-kV switching power supply and is in use at SLAC as a test stand for klystron development and evaluation. For the NLC, the very large number of modulators required made electrical efficiency the key criterion for comparing modulator designs. The hybrid modulator operates at 75%–80% efficiency into its klystrons, significantly higher than competing technologies examined by SLAC.[1]

Submicrosecond risetime is a major challenge for a hybrid modulator, due to the inductance seen by the switch at the primary of the pulse transformer. As the transformer ratio increases, the primary current increases, while the primary driving voltage drops. Thus, the equivalent inductance increases as the *square* of the transformer ratio for fixed risetime. The objective, therefore, was optimizing the transformer ratio and the solid-state switch size to achieve the required pulse performance. For the NLC, for example, our design compromised on a 6.33:1 transformer ratio. This ratio was chosen because it falls within a relatively broad life-cycle cost minimum, the 80-kV primary voltage was easily within the capabilities of the existing technology, and the 3,500-A primary current, although challenging, was reasonable

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[†] DTI's architecture combining solid-state switches and a pulse transformer in a high-power pulse modulator.

[‡] Now transitioned to the International Linear Collider (ILC) program.

for the desired NLC pulse risetimes. The following sections describe this design in more detail. Other DTI hybrid modulator designs have used higher transformer ratios (to ~12:1) to simplify the primary switch and optimize the overall size and cost of the pulse modulator.[§]

2.3. Solid-state switch

To facilitate the fast risetime needed for the NLC klystrons, the switch was constructed utilizing "stripline" architecture. In this architecture, a series of solid-state switches are arranged on a bus with an impedance-matched return strap imaged on the other side of an 80-kV polyethylene insulator. The remainder of the modulator system, filter capacitors, control systems, heat removal, snubber diodes, and auxiliary power systems for filaments and core bias, was added around this switch/transformer foundation. The transformer was wound with a quadrifilar secondary to accommodate independent filament windings for each of two parallel klystron loads.

The bare solid-state switch is composed of 24 series switch modules,[¶] each rated for a dc holdoff of 4.5 kV and capable of repetitive pulsed currents of 5 kA. The switch modules are capable of opening safely at fault currents of up to 10 kA without damage and will accommodate risetimes greater than $dI/dt \sim 5$ kA/μs without undue internal losses. These risetimes are sufficiently fast that the pulse risetime of the hybrid modulator *system* is dominated by the parasitic system impedances, not by the solid-state switch.

In keeping with DTI's robust commercial architecture, the switch modules are powered inductively and controlled via fiber-optic isolated signals. The switch controls are fully protected against overcurrent, overvoltage, and pulse demand violations through hardwired programmed-logic control networks. The high-voltage elements of the system are immersed in transformer oil for high-voltage isolation and heat removal, while the controls are accessible above the tank. The entire unit can be removed from oil without disconnecting any controls or interlocks.

Figure 5 shows the intrinsic risetime capabilities of the hybrid NLC system into a 990-Ω dummy load during preliminary testing at DTI. The secondary voltage data and SPICE model (offset by 50 kV) are shown in Fig. 5a for a test pulse. The primary voltage was 83 kV, and the load 990 Ω, with the bouncer components removed. The overshoot is entirely due to the difference between resistive and klystron loading. This demonstrates that the modulator operates as designed and that the modeled circuit agrees extremely well with the actual results. The SPICE model of the hybrid modulator secondary voltage into the nonlinear klystron load is shown in Fig. 5b. The risetime is 660 ns (10%–90%), or 1.0 μs (0%–97%). Note that the pulse flatness easily meets the ±3% specification. This performance has subsequently been confirmed by SLAC in klystron operation.[3]

2.4. Incrementally corrected Marx modulator

A Marx bank modulator is an array of capacitors charged in parallel (at low voltage) and then switched in series to form a high-voltage discharge. A simple schematic is shown in Fig. 6. This has the advantage of requiring dc power at a voltage much lower than that delivered to the load; indeed there is no dc present at load voltage anywhere in the system.

[§] A high-power electronic switch used to modulate pulse power with very high precision. DTI's modulators employ solid-state switches, rather than vacuum tubes.

[¶] DTI terminology for a set of lower voltage solid-state devices (usually FETs or IGBTs) arranged in series and acting as a single higher voltage switch. A switch module can be rated from approximately 3 kV to 10 kV.

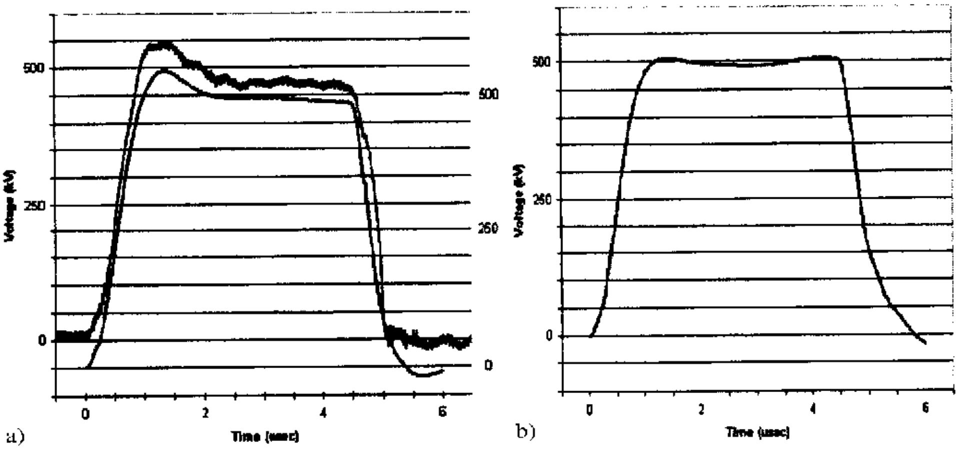

Fig. 5. Secondary voltage data (a) and SPICE model (offset by 50 kV) (b) for a test pulse of the hybrid modulator.

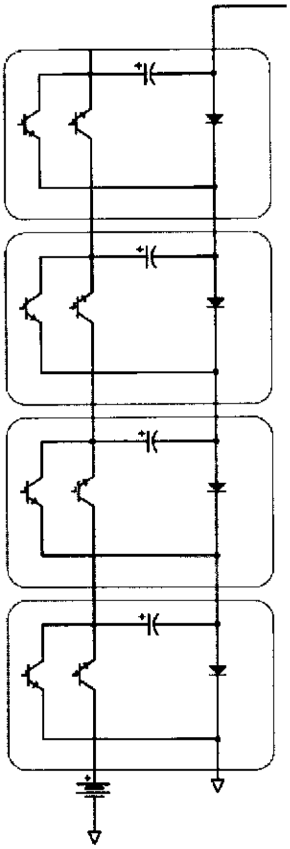

Fig. 6. Four-stage solid-state Marx bank modulator (with switched recharge).

Traditional Marx modulators use "closing" switches (i.e., silicon controlled rectifier or spark gaps) to make the series connection and erect the high-voltage (HV) stack of capacitors. Thus, the stored charge must be fully exhausted and replenished each pulse, and a pulse-forming network is required to shape the output. A solid-state Marx modulator uses IGBTs or field effect transistors (FETs) that can open under load; thus the capacitor stack becomes a filter/storage bank analogous to that of a solid-state hard switch modulator.

The Marx architecture is a convenient way of using devices with intrinsic limits of a few kilovolts to erect very large pulses. Unfortunately, the cost and efficiency of the system suffer if the unit voltage is too low. The repeated overhead at each stage, and the ohmic losses of the higher current recharge, make this option unattractive for voltages beyond 40–60 kV. Using DTI's series IGBT technology to assemble single modules of higher unit voltage avoids this issue. This does not affect the *overall* size of the system but significantly affects the size, number, and complexity of the switching modules and allows for greater optimization of the complete design.

Recharge of the capacitors in parallel during the interpulse period can be accomplished by one of several means, each of which has advantages for certain classes of performance:

- A chain of resistors is the simplest recharge scheme but is limited to only very low duty cycle and power.
- A diode/inductor network allows average current to recharge while blocking HV discharge during the pulse, but is limited to low duty cycle and short pulse.
- A common-mode choke scheme recharges faster and thus works at higher duty cycle, but is still limited to short pulse.
- A second bank of switches, like that shown in Fig. 6, can be used for arbitrary duty cycle and power, but at higher cost and complexity.

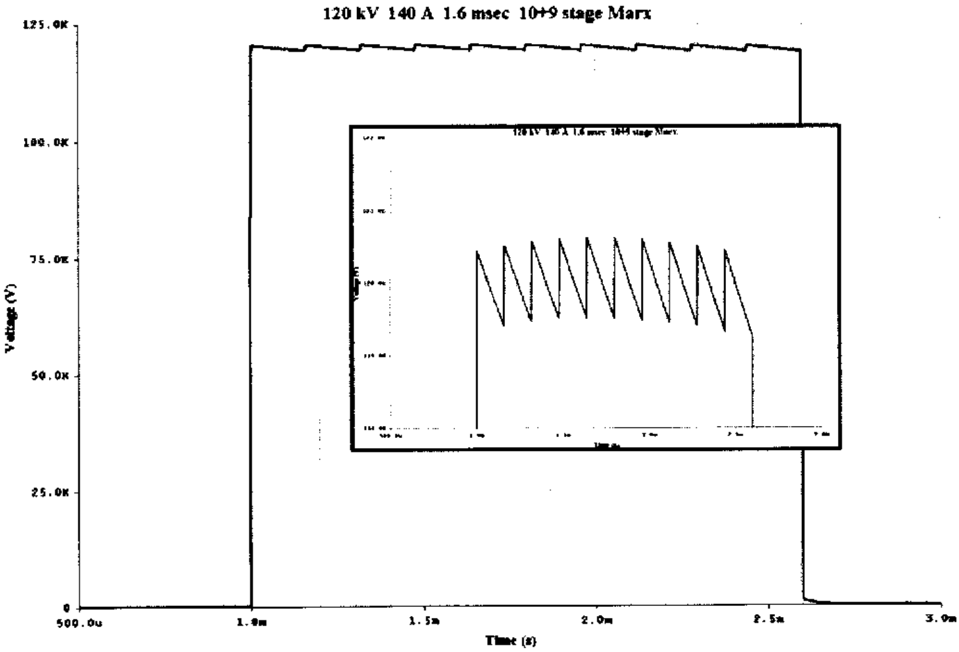

Fig. 7. Staggered module switching to compensate for capacitor droop during the pulse.

Any of these schemes can also be configured to fire the switches independently. Any section that is not turned on is bypassed by a diode; thus the pulse voltage is simply lower by the potential of that stage. This capability can be used to correct for the droop of the energy storage bank, as shown in Fig. 7.

At high voltage and high power (hundreds of kilowatts average power) the use of ~10-kV modules allows many systems to greatly reduce the cost and size of the dc input section. Power from medium voltage (13.8-kV ac) distribution can be rectified directly, eliminating the need for large power supplies and step-up transformers. A solid-state buck regulator is used to step down this unregulated, rectified voltage to a regulated ~10-kV recharge voltage. These dc–dc conversions use "off the shelf" technology and typically perform at 95% or better efficiency.

3. Conclusion

Operational DE systems will require reliable, compact pulsed power systems, with high reliability and low maintenance requirements. The development of solid-state technologies for high-energy physics by the DOE has brought this technology to a point where it can readily be applied to DE systems. As demonstrated by the modulator developments for the NLC and ILC, multiple solid-state architectures can be used to optimize the pulsed power delivery to the load. The major remaining issues that must be resolved to enable fielding of these systems are primarily focused on packaging this technology into compact, deployable configurations to meet the warfighter's requirements.

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