

RECENT DEVELOPMENTS IN PULSED HIGH POWER SYSTEMS*

David E. Anderson, ORNL, Oak Ridge, Tennessee, USA

Abstract

Pulsed power systems are inherent in any high power accelerator system. Applications include, among others, modulators for powering high power klystrons, pulsed power systems to drive linear induction accelerating cells, kicker magnet drivers for storage rings, and a wide variety of beam deflection and pulsed focusing systems. As with many enabling technologies, component limitations and materials properties dominate the engineering tradeoffs that must be made during the system design. An overview of the state-of-the-art in major components of pulsed power systems will be presented. An examination of how those components are being integrated into linac systems will also be performed and an overview of these systems shall be given. The relatively recent shift toward solid-state power electronics solutions to pulsed power engineering problems will be emphasized. Finally, some future trends in the field will be examined.

INTRODUCTION

Pulsed power is a broad, multi-disciplinary field that focuses on compressing electrical energy in time and expanding it into high peak power pulses. Although techniques for generating electrical pulses of large amplitudes existed prior to World War II, the development of equipment to drive magnetron oscillators for microwave radar started the field of pulsed power [1]. Since that time, applications have been dominated by defense-related technologies, primarily in the area of weapons simulators, charged particle beam diodes, directed energy weapons, and others. However, several non-defense applications have also arisen, including particle accelerators, fusion systems, effluent treatment devices, and a myriad of biomedical applications, to name a few [2].

Over the past decade or two, significant advances in new solid-state devices and improvements in high energy density components have led to a reduction in sizes of pulsed power systems [3]. Also, developments in these areas have allowed engineers to take advantage of techniques and topologies typically reserved for the field of power electronics, resulting in more efficient systems. As these improvements continue, led by developments in industry and through continued military R&D, more commercial applications of compact pulsed power systems will continue to appear. In the field of accelerators, this will result in higher reliability systems with excellent efficiencies rivaling switch mode power supplies requiring less-frequent maintenance cycles. While developments in the field of pulsed power extend beyond accelerator systems employing recent technologi-

cal innovations, due to space constraints, this paper will attempt to focus and highlight that particular area of development.

ENABLING TECHNOLOGIES: CURRENT TRENDS IN DEVICES & COMPONENTS

The system is only as good as the sum of its parts, and like most enabling technologies, materials properties dominate the component limitations. Most of the device improvements have not come directly from pulsed power-related application but from related fields with larger economic markets such as variable speed motor drives, switch mode power supplies, and power factor correction circuits, to name a few. Fortunately, vendor-customer cooperation is very good, and many hybrid devices have yielded satisfactory results [4].

Capacitors

Since the days of the Kraft™ paper/foil capacitors, this technology has undergone many changes. Figure 1 shows the improvement in energy density in the last 30+ years for state-of-the-art energy discharge capacitors, much of which is a result of improvements in manufacturing techniques and materials [3][5][6]. Historically, capacitor technology advances at a factor of about 2× per decade for traditional capacitors and up to 18× per decade for high energy capacitors for any performance factor not approaching natural limits [5], although there appears to be a reduction in energy density improvement in recent years.

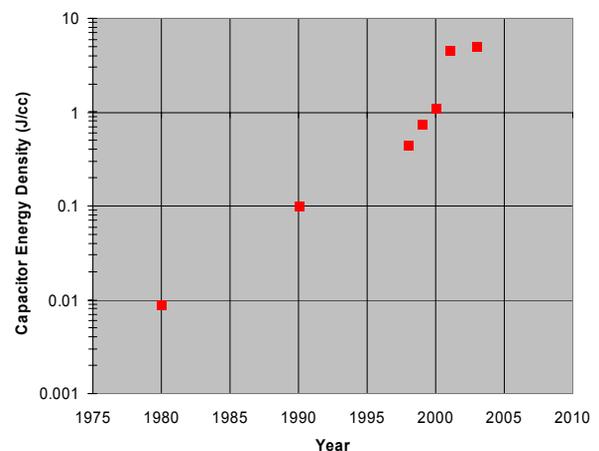


Figure 1: Evolution of Capacitor Energy Density over Time

Most of the recent improvements are the result of the use of metallized polymer film windings. This technology, while limited in deliverable peak current, allows for higher operating dielectric stresses due to the self-clearing nature of the design. A 15th power aging rate

*ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725

dependence on voltage allows for tremendous increases in capacitor lifetime with minimal voltage deratings and negligible infant mortalities compared with previous energy discharge capacitors [5]. Typical designs define end-of-life as a 5% degradation of capacitance, after which time gas accumulation and case bulging provide other indications of the need for replacement [7].

Recent work by Huazhong University on multilayer ceramic capacitors has yielded units capable of surviving 10+ million discharges with energy densities on the order of 0.5 J/cc. While the BaTiO₃ X7R dielectric displays some possibly undesirable characteristics due to the nonlinear charge/voltage relationship and ferroelectric hysteresis, these may be acceptable in certain applications and continued development may improve the device properties [8].

Solid-State Switches

Since the initial development of the transistor in the late 1940s, solid-state switches have continued to evolve. In 1982, B.J. Baliga invented the insulated gate bipolar transistor (IGBT), dramatically increasing the power handling capability of moderately fast switching devices [9]. Present state-of-the-art IGBT devices are capable of switching 6.1 MW (1700 V / 3600 A) continuous duty, with a peak power rating double that for 1 ms switching, although devices rated up to 6500 V at lower currents are available [10]. Fractional microsecond switching speeds permit applications up to approximately 20 kHz, although the devices are typically designed for much lower operating frequencies.

For higher frequency switching applications, MOSFETs are still the preferred component. Presently limited to peak operating voltages of 1000-1200 V and maximum currents of less than 100 A, switching times can be on the order of 10 ns at these levels. The device conduction losses, with $RDS_{on} \sim V_{bd}^{2.6}$, presently limits peak current [11]. However, a new generation of super junction MOSFETs has appeared and exhibits a linear relationship between blocking voltage and on-state resistance as well as offering lower device capacitances [12]. This will allow lower losses, easier thermal management, and smaller device packaging for future designs.

Another area of rapid advancement is that of silicon carbide devices which exhibit a 10× improvement in breakdown electric field, 3× increase in thermal conductivity, 3× band gap energy, and double the saturated electron velocity compared to silicon [13]. Schottky diodes, JFET/Si MOSFET Cascode hybrids, FETs, MOSFETs, and GTOs are available commercially or in development [14]-[16]. As freewheeling diodes across MOSFETs or IGBTs, SiC Schottky diodes offer significantly lower reverse recovery charge, resulting in lower switching losses as shown in Figure 2. Pulsed power capacitive discharges over 3000 A for several microseconds in a single 16A SGTO device for 14,000 shots have also been reported [16]. 1 MHz burst mode operation of SiC FETs has been demonstrated at 1000 V by Jiang and colleagues [17].

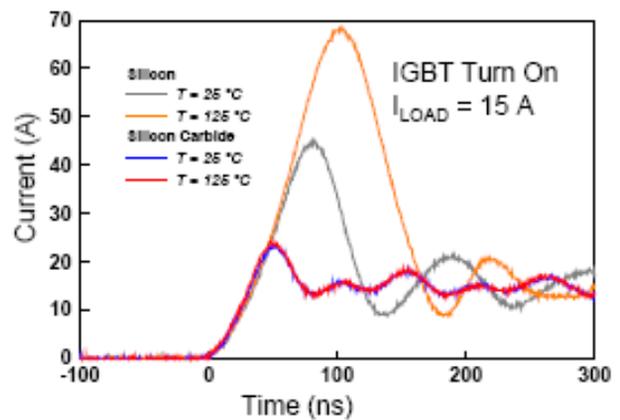


Figure 2: Comparison between Silicon and Silicon Carbide Freewheeling Diode in IGBT Losses

Magnetic Materials

The advent of a new nanocrystalline SiFe alloy has been the largest advance in magnetic materials. This material combines the high saturation magnetic flux density of the well-known silicon steel with the low high-frequency losses comparable to MnZn ferrites and permalloys. It also has the advantages of exhibiting almost zero magnetostriction as well as hysteresis loss and permeability stability over a wide range of temperatures [18]. Packing fractions approaching 85% can be achieved using the NAMLITE® insulation coating system [19].

SYSTEM REALIZATIONS: COMPONENTS IN ACTION

The applications of these new technological innovations since the turn of the century have been quite numerous. Applications include replacement of thyristors with solid-state switch arrays, application of these new innovations to old pulsed power topologies, extension of traditional converter and regulator topologies to higher voltage and power levels, and implementation of some novel concepts.

Traditional Techniques with Solid-State Twists

The Fermi-DESY “bouncer” modulator circuit, originally developed to test multi-beam long-pulse klystrons, utilizes an IGBT series switch in a closing/opening configuration to deliver an adjustable-width pulse at 110 kV and 130 A. The series stack of 12 IGBTs achieves the switching function, and a second circuit, consisting of a resonant tank circuit at lower voltage, provides droop compensation to make up for the ~20% droop from the capacitor discharge [20]. This technology is currently undergoing modernization to support the International Linear Collider (ILC) project [4]. The CERN team has developed a IGBT-based kicker system for measuring betatron tune which employs a new press-pack capsule IGBT modules rated at 5200 V and 1180 A. These new devices offer no bonding wires or

soldering bonds, reducing the stray inductance which should yield more reliable snubberless operation [21].

To satisfy the stringent German requirement of <0.5% line voltage variation, a superconducting magnet energy storage (SMES) modulator system is under development at the TESLA test facility. The system is capable of delivering up to 130 kV pulses to drive a 10 MW klystron. Pulse widths of up to 1.7 ms and a rep rate of up to 10 Hz are possible. The modulator takes advantage of the high conduction current characteristics of the IGCT devices, rated for 2.6 kA at 14 kV, to deliver energy stored in the superconducting coil to a 13:1 stepup transformer. The large inductance of the primary energy store naturally limits fault currents, thereby eliminating the need for a crowbar circuit with this topology [22].

Replacement of existing thyratrons with solid-state arrays is gaining popularity. A 45 kV array of Si-thyristors, capable of switching 6000 A at 10 kA/μs, was built by the KEK team [23]. Using similar devices, a test stand capable of switching 10 kV at 1.8 kA with a risetime of 120 ns for the KEK kicker systems has been demonstrated [24]. Another system uses IGBTs in a series array rated at 35 kV, 700 A, and achieves a ~300 ns risetime. This kicker pulser only requires direct gating of the ground-referenced switch, with the remaining series switches being gated by receivers which detect the induced displacement currents to achieve a <5 ns switch jitter [25].

Solid-State Marx Generators

As a competing modulator technology for the ILC solid-state Marx generators are currently being developed in the United States. Lower voltage versions, operated to 20 kV at 300 A, 5 μs to 1 kHz, have been developed in Korea [26]. The basic scheme, shown in Figure 3 below, incorporates medium voltage charging through isolation elements (“charge switch” shown in the figure) to allow for parallel capacitor charging as in traditional Marx generators and a series “firing” switch to erect the Marx to produce the desired output pulse. Fast diodes are installed in parallel with the switch/capacitor sections to “bypass” a stage if the switch fails to fire, increasing the overall system reliability. Originally designed to support the short-pulse baseline design, the systems used isolation inductors to provide DC charging paths and provide for the transfer of filament power to the klystron gun [27]. Further enhancements included the inclusion of solid-state switches in the charging circuit to isolate sections if component failures were to occur and utilization of 2.4 GHz wireless communication links to carry timing and control data [28].

With the selection of a superconducting cavity baseline for the ILC, a long-pulse (~1.5 ms) variant of the solid-state Marx had to be developed. Both designs now employ a second bank of switches for charging as shown in Figure 3 [29]. Also, with the longer pulse and the droop requirements, the amount of on-board capacitance became prohibitively large. Compensation for the pulse droop is now provided by additional Marx stages that

operate at lower voltages (~1 kV) and are fired sequentially throughout the main pulse to correct for the droop. Use of a solid-state buck regulator, operating directly off the rectified 13.8 kV line, eliminates the need for an additional power conversion stage and improves the overall system efficiency [30].

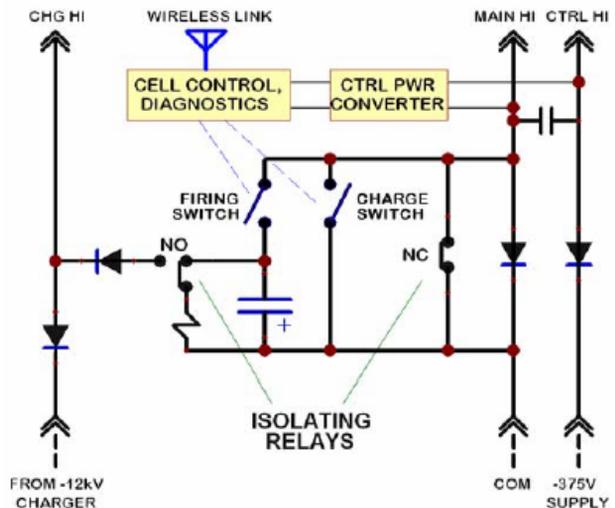


Figure 3: Solid-State Marx Generator Representative Stage Schematic

Inductively-Coupled Schemes

Cook and colleagues have developed a modular inductive voltage adder scheme which has been applied to a variety of applications as shown in Figure 4. MOSFETs and IGBTs have both been used, depending on the switching speed and current requirements. The technology has the advantages of the drive components being at ground-referenced potential and can deliver a wide array of pulses at high burst frequencies over a variety of load impedances. However, to achieve fast switching and deliver high load currents, careful circuit layout to minimize parasitics and low jitter devices are a necessity. Diode clamping snubbers minimize switch damage, and fast diode clamps provide a path for magnetizing currents as well as offer core reset features. Units capable of producing 20 kV into 50 Ω switching in ≤10ns and delivering 500 kV at 600 A for a 3 μs pulse have been built and tested [31].

While not strictly a magnetically-coupled modulator topology, the induction synchrotron utilizes induction cells to accelerate and confine RF bunches in a ring. A proof-of-principle H-bridge modulator system has been constructed and tested at a continuous repetition rate of 1 MHz, delivering 2.5 kV bipolar pulses to a 100 Ω load with 250 ns pulsewidths. Rise and falltimes demonstrated were 20 and 25 ns, respectively [24].

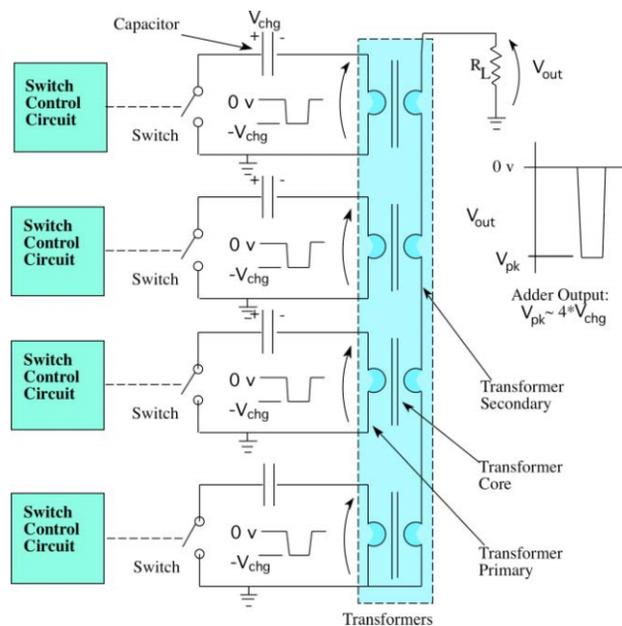


Figure 4: Inductive Voltage Adder Solid-State Modulator (4 Cell shown)

High Power Converters and Regulators

The most well-known example of application of traditional converter topologies to higher powers is the Spallation Neutron Source modulator [32]. This system utilizes a large capacitive energy store and delivers the energy to a 3-phase resonant boost transformer, where the resulting waveform is rectified and filtered to produce a 1.35 ms pulse at up to 140 kV to power klystron(s). Boost transformer primaries are driven by an IGBT H-bridge with bipolar 20 kHz pulses to minimize core volt-second requirements. Resonance is achieved with the transformer leakage inductance and an external capacitor across the secondary, resulting in soft switching of the IGBTs. Detuning of the resonant circuit occurs during load faults, thus eliminating the need for crowbar circuits. All fast fault protection, gate drive pulse generation, and feedback/adaptive feedforward functions are performed in a custom DSP-based controller unit. Long-term operation of these systems has revealed some limitations, and upgrade programs are in process [33].

A similar approach is described at the University of Nottingham for a lower voltage application to deliver 25 kV at 10 A [34]. An intelligent recharge of the DC energy storage capacitors between pulses is proposed to minimize flicker on the utility feed. Utilization of phase-shift and frequency modulation techniques are used to minimize switching losses and result in a lower energy storage capacitor requirement over the SNS modulator [35]. To date, tests have only been performed on a ~2000 V circuit operating at similar output power levels utilizing feedforward control only.

CONCLUSION

Critical advancements in several areas key to pulsed power, driven by commercial applications, have resulted

in a new class of devices designed to meet specific accelerator-based applications. All of these applications discussed owe their success to the significant improvements in high power semiconductor devices that have occurred over the last decade. While there are still applications where traditional vacuum electron devices cannot yet be replaced, the advancement of solid-state devices is quickly catching up and may someday replace those devices. The demand for more compact, higher density systems for military and airborne applications should force the enabling technologies to keep pace with the semiconductor switches, resulting in size reduction and efficiency improvements in all future systems.

REFERENCES

- [1] G. N. Glasoe and J. V. Lebacqz, *Pulse Generators*, New York, NY: McGraw-Hill Book Company, 1948.
- [2] E. Schamiloglu, R.J. Barker, M. Gundersen, and A. A. Neuber, "Scanning the Technology Modern Pulsed Power: Charlie Martin and Beyond," *Proc. IEEE*, Vol. 92, No. 7, July 2004, p. 1014-1020.
- [3] M.V. Fazio and H.C. Kirbie, "Ultracompact Pulsed Power," *Proc. IEEE*, Vol. 92, No. 7, July 2004, p. 1197-1204.
- [4] R. Cassel, private conversation, July 2006.
- [5] W.J. Sarjeant, J. Zirnheld, and F.W. MacDougall, "Capacitors," *IEEE Trans. Plasma Science*, Vol. 26, No. 5, October 1998, p. 1368-1392.
- [6] F.W. MacDougall, J.B. Ennis, R.A. Cooper, J. Bates, K. Seal, "High Energy Density Pulsed Power Capacitors," *Proc. IEEE Pulsed Power Conf.*, June 2003, Dallas, TX, p. 513-517.
- [7] G. Terzulli and B.W. Peace, "Film Technology to Replace Electrolytic Technology," [Online], available: <http://www.avxcorp.com/docs/techinfo/filmtech.pdf>.
- [8] L. Dai, F. Lin, Z. Zhu, and J. Li, "Electrical Characteristics of High Energy Density Multilayer Ceramic Capacitor for Pulse Power Application," *IEEE Trans. Magnetics*, Vol. 41, No. 1, January 2005, p. 281-284.
- [9] B.J. Baliga, M.S. Adler, P.V. Gray, R.P. Love, and N. Zommer, "Insulated Gate Rectifier (IGR); A New Power Switching Device," in *Proc. Tech. Digest IEDM*, 1982, p. 264-267.
- [10] U. Schwarzer and R.W. DeDoncker, "Characterization of 6.5 kV IGBT Modules for Hard- and Soft-Switching Operation in Medium Voltage Applications," *Proc. APEC*, 2005, p. 329-335.
- [11] I. Bencuya, "The Future of Power Semiconductors," *Proc. APEC*, 2005, p. 18-24.
- [12] G. Deboy, M. März, J.-P. Stengl, H. Strack, J. Tihanyi, and H. Weber, "A New Generation of High Voltage MOSFETs Breaks the Limit Line of Silicon," *Proc. IEDM*, 1998, p. 683-685.
- [13] J.C. Zolper, "Emerging Silicon Carbide Power Electronics Components," *Proc. APEC*, 2005, p. 11-17.

- [14] A. Agarwal, et. al, "600 V, 1-40 A, Schottky Diodes in SiC and Their Applications," [Online], available: <http://www.cree.com/products/pdf/PWRTechnicalPaper1.pdf>
- [15] D. Stephani, "The Industrial Utilization of SiC Power Devices – Aspects and Prospects," Workshop on Future Electron Devices, March 2003, Yokohama, Japan.
- [16] H. O'Brien, W. Shaheen, and S.B. Bayne, "Evaluation of a 4 mm × 4 mm SiC GTO at Temperatures up to 150 °C and Varying Pulse Width," submitted to IEEE Power Modulator Conference, May 2006, Washington, D.C.
- [17] W. Jiang, et. al, "Pulsed High-Voltage Modulators Using Power Semiconductor Devices," submitted to IEEE Power Modulator Conference, May 2006, Washington, D.C.
- [18] M. Ferch, "Light Transformers for Kilowatt SMPS Based on Nanocrystalline Softmagnetic Cores," Proc. Power Electronics and Variable Speed Drives, 1998, p. 411-415.
- [19] T. Slattery, "A New Insulation Coating for Amorphous and Nanocrystalline Alloy Tape-Wound Cores," Proc. Intertech International Soft Magnetics Conference, May 2000, Dearborn, Michigan.
- [20] H. Pfeffer, et al., "A Second Long Pulse Modulator for TESLA Using IGBTs," EPAC, June 1996.
- [21] E. Carlier, L. Ducimetière, E. Vossenber, "A Kicker Pulse Generator for Measurement of the Tune and Dynamic Aperture in the LHC," submitted to IEEE Power Modulator Conference, May 2006, Washington, D.C.
- [22] K-P. Juengst, R. Gehring, A. Kudymow, G. Kuperman, and E. Suess, "25 MW SMES-Based Power Modulator," IEEE Trans. App. Superconductivity, Vol. 12, No. 1, March 2002, p. 758-761.
- [23] M. Akemoto, H. Honma, and S. Anami, "High-Power Switch with SI-thyristors for Klystron Pulse Modulators," Proc. Power Modulator Symposium, 2000, p. 205-208.
- [24] W. Jiang, et al., "Compact Solid-State Switched Pulsed Power and Its Applications," Proc. IEEE, Vol. 92, No. 7, July 2004, p. 1180-1196.
- [25] Y. Ishi, Y. Mori, M. Muto, Y. Shirakabe, A. Takagi, "High Repetition Beam Kicker with IGBT Switching Modules," Proc. PAC, 2001, Chicago, p. 4053-4055.
- [26] J.W. Baek, D.W. Yoo, G.H. Rim, and J. Lai, "Solid State Marx Generator Using Series-Connected IGBTs," IEEE Trans. Plasma Science, Vol. 33, No. 4, p. 1198-1204.
- [27] J.A. Casey, F.O. Arntz, M.P.J. Gaudreau, M.A. Kempkes, "Solid-State Marx Bank Modulator for the Next Linear Collider," Proc. EPAC, 2004, Lucerne.
- [28] G.E. Leyh, "Prototype Development Progress Toward a 500 kV Solid State Marx Modulator," Proc. EPAC, 2004, Lucerne.
- [29] G.E. Leyh, "The Marx Modulator Development Program for the International Linear Collider," submitted to IEEE Power Modulator Conf., May 2006, Washington D.C.
- [30] I. Roth, J. Casey, N. Butler, M. Kempkes, M. Gaudreau, "Solid-State Modulators for the International Linear Collider," submitted to the IEEE Power Modulator Conf., May 2006, Washington D.C.
- [31] E.G. Cook, et al., "Solid-State Modulators for RF and Fast Kickers," Proc. PAC, 2005, Knoxville, TN, p. 637-640.
- [32] W.A. Reass, et al., "High-Frequency Multimegawatt Polyphase Resonant Power Conditioning," IEEE Trans. Plasma Science, Vol. 33, No. 4, p. 1210-1219.
- [33] D.E. Anderson, J. Hicks, M. Wezensky, D. Baca, and W. Reass, "Operational Performance of the Spallation Neutron Source High Voltage Converter Modulator and System Enhancements," submitted to IEEE Power Modulator Conference, May 2006, Washington, D.C.
- [34] M.J. Bland, J.C. Clare, P.W. Wheeler, "Multiphase Resonant Power Converter for High Energy Physics Applications," Proc. EPAC, 2006, Edinburgh, Scotland, p. 2658-2660.
- [35] M.J. Bland, J.C. Clare, P.W. Wheeler, J.S. Pryzbyla, "A High Power RF Power Supply for High Energy Physics Applications," Proc. PAC, 2005, Knoxville, Tennessee, p. 4018-4020.