High Power, 10 kHz Repetition Rate Ultra-wideband Source Development at the U.S. Army's Missile Command

Daniel Birx
Science Research Laboratory

Jerome R. Fishback
U.S. Army Missile Command

ABSTRACT

A 250 MW ultra-wideband source capable of pulse repetition frequencies up to 10 kHz has been developed at the U.S. Army's Missile Command (MICOM). This modular pulser utilizes state-of-the-art magnetic switch pulse compression and electromagnetic shock line pulse sharpening to produce highly reliable 3 ns pulses with rise times less than 200 ps. ERP's of up to 0.75 GW have been achieved using TEM horns.

INTRODUCTION

The requirements for sources of wide band RF have undergone significant changes within the last few years, the most notable of which is the requirement of high repetition rate capability. The single pulse characteristics of these systems have long been characterized as having pulse widths of several nanoseconds and sub-nanosecond rise times. Recent advances in technology have extended the capability of some systems, with reduced power, to produce sub-nanosecond pulse widths and rise times less than 100 ps. The particular application determines the required temporal characteristics of the source, while the technology available to produce those characteristics may largely determine the pulse power and repetition rates available.

To date, technologies which have been pursued to meet these requirements include repetitive spark gaps, thyratrons with shock line pulse sharpening, and photoconductive switches. This paper discusses the development of an all solid state, SCR commutated, non-linear pulse compressor which utilizes an electromagnetic shock line to produce 250 MW pulses with 4 ns pulse widths and rise times less than 200 ps. This system is capable of repetition rates up to 10 kHz for burst durations of up to several seconds. The theory of non-linear magnetic pulse compressors, or "magnetic switches", is well documented [1-9], and the discussion will be limited to the performance of this system.

SYSTEM OVERVIEW

SCR commutated magnetic switch pulse compressors have been used for several years to produce high energy pulses of up to several hundred joules with 50 ns pulse widths at repetition rates in excess of 5 kHz. These systems have been highly reliable (lifetimes of 10^{11} to 10^{12} shots), have very little jitter, and are capable of continuous operation. To extend their application to wide band RF, two to three stages of additional pulse compression are required to reduce the pulse width. A shock line is then utilized to produce the necessary fast rise time.

Though three separate modulator designs have been upgraded to date, the system presented in this paper is the latest version of a modular design with and input energy of approximately 8 joules. This system is readily maintained and can be easily handled by two people. Its subsystems include the control and command resonant charge chassis; two rack mountable chassis, each containing two commutator modules; an oil cooled compression module; and an electromagnetic shock line with a PFL interface to the modulator (fig. 1).

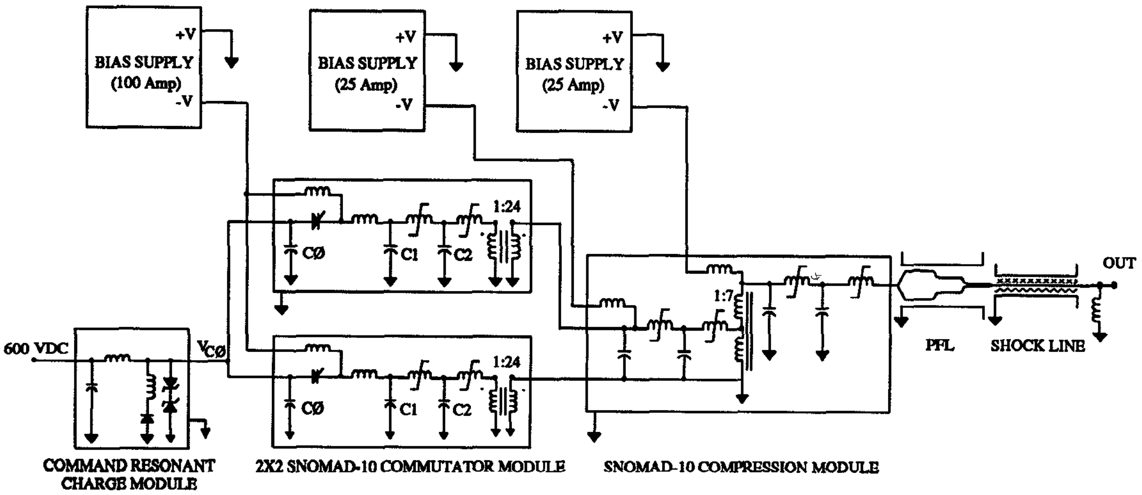

Figure 1: System Block Diagram

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CONTROL AND CHARGE CHASSIS

The reliability of the SCR commutated magnetic pulse compressor is determined primarily by the performance of the main commutator SCR's. To assure that adequate trigger signals are supplied to the SCR's at the proper times, a control chassis containing timing and protection circuitry supplies the appropriately timed triggers to the charge chassis and commutator modules. Monitor levels from the power supply voltage and resonant charge level prevent triggering when these levels are too low or to high, respectively. The input to the control chassis is TTL.

The charge chassis is a conventional resonant charge system. It uses a single R-355 SCR to deliver 8 joules in approximately 20 us to the intermediate storage capacitors of the commutator modules (fig. 2). The recovery time of these SCRs is approximately 45 us and is the limiting factor in the prf capability of these systems. Work is currently being done to extend the prf capability to 30 kHz by replacing these SCRs with insulated gate bipolar transistors (IGBTs). The input voltage is a nominal 500 to 575 volts with a resonant gain set to approximately 1.8. The maximum charge level is limited by an 1100 volt zener stack which protects the main SCR's from overvoltage. During operation, energy reflected from each pulse due to load mismatches is recovered via an inductive storage circuit. The recovered energy is added to the next pulse, reducing the load required of the charging SCR. For high PRF's, the load requirement can be further reduced by installing a second charge system in parallel within the same chassis.

COMMUTATOR MODULES

The four commutator modules contained within the two chassis are each an individual PCB-mounted, SCR commutated magnetic pulse compressor. Employing a technology known as "Branched Magnetics", these modules are operated in parallel with the outputs combined in series. This design provides for the system's highly reliable operation, in that the maximum voltage appearing anywhere in the input module is less than 1000 volts. At the end of a charge cycle, a single R-355 SCR on each board is used to transfer 2 joules in 7 us from the intermediate storage capacitors to the first of two compression stages in the module. These stages utilize single-turn 2605-SC Metglas cores for the saturable inductors and provide a temporal gain of 13 and 3, respectively. The cores are housed in tightly fitting coaxial housings to reduce losses. The 4 uf capacitor banks used for these stages and the intermediate storage are comprised of low loss, high reliability, aluminized polypropylene capacitors with a demonstrated shot-life in excess of 10^{11} for this application. The output of the second stage is delivered in 180 ns to the primary of a 1:12 induction transformer. The two transformers in each chassis are summed via a conducting rod placed down the center of the induction cells. The output of this rod drives the input stage of the compression module.

COMPRESSION MODULE

The compression module consists of four stages of pulse compression with a 1:7 induction style transformer between the second and third stages. This transformer utilizes a fractional turn primary and single turn secondary, a novel design accredited to Nicholas Christofolis who originally used it in charged particle beam research. The initial two stages and transformer are housed within an aluminum cylinder, while the final two stages are constructed of o-ring sealed cylindrical aluminum plates. Oil flow through this assembly provides both cooling and high voltage insulation.

The saturable inductor of the input state is constructed of 2605-SC Metglas. When this stage saturates, it charges the 7.2 nf second stage capacitor bank to 30 kV in 28 ns. At these time scales, Metglas can no longer be used. The remaining stages therefore employ CMD-5005 ZnNi ferrite cores. The gain of these stages is also reduced to lower both the losses and the required volume of magnetic material. Bus plate capacitors are used for the last two stages. Derivative E-dot probes located on the cylinder wall around the bus plates provide measurements of the waveforms at those points. When the final stage saturates, approximately 2 joules are delivered in 3.5 ns to the matching PFL of the shock line (fig. 2). This produces a traveling gaussian wave of 3.5 ns pulse width, which represents the limit of compression currently achieved with magnetic pulse compression technology.

Because the impedance of each compression stage decreases by the square of the temporal gain for that stage, the output of these systems is traditionally suited for driving low impedance loads. However, the impedance of the magnetic shock line is relatively high, with saturated impedances designed to match that of conventional coaxial cable (50 Ω). A coaxial PFL with an input impedance matched to that of the output stage of the compression module (5 to 15 Ω) transforms the impedance up to that of the shock line. This transformer action also produces a voltage gain of approximately 2.

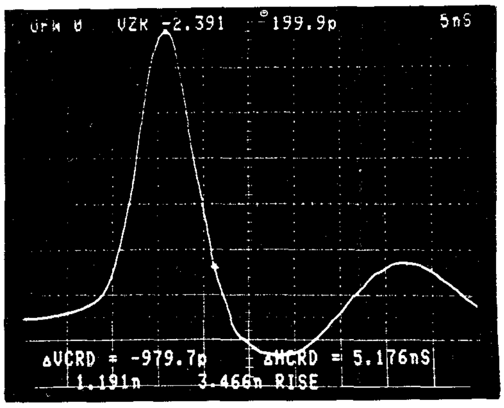

Figure 2. Integrated measurement of waveform on final bus plate of compression module.

ELECTROMAGNETIC SHOCK LINE

The final sub-system incorporates electromagnetic shock line technology [10] to produce a rise time of less than 200 ps. The shock line is a 40 inch, ferrite filled transmission line with a saturated output impedance of 50 Ω. The difference between the "magnetic switches" and the shock line lies in the fact that the switches saturate as a single volume, while the shock line has at any one time only a region along its length that is undergoing saturation. As with any other shock wave phenomena, the velocity of the wave varies along its rising edge. In the case of the shock line, the velocity of the wave front varies with the inverse of the square of the permeability. The crest of the wave front, where the ferrite is completely saturated (i.e. m -> 1), therefore travels at a greater velocity than that of the incident rising edge. The output of the shock line has a much sharper rise time than the input, while the fall time is somewhat extended. The drawback of using a shock line is that roughly one half of the energy is thrown away; however, that is the cost of using this technology in that there is currently no alternative to produce the fast rise times desired for this application.

The output of the shock line (fig. 3) is a 150 kV, 4 ns pulse with a rise time of less than 200 ps. This pulse is launched into a coaxial cable (RG-177) which delivers the pulse to an appropriate antenna. For the work performed at MICOM, several TEM horns have been developed for use with this system. To date, these have been low gain (< 2 dB) antennas in order to produce broad uniform fields within ranges of several tens of feet. The most recent has an oil-filled coaxial-to-flat plate unfolding feed section, a plate impedance of 120 Ω, and has produced fields of 12 kV/m at 12 meters (fig. 4). A D-dot ground plane probe mounted on the plates measured an approximate peak level of 200 kV (fig. 5). Using an isotropic, lossless antenna as a reference, this indicates that the system had a power gain of 3 dB and an ERP of 660 MW. A crude field modification to increase the gain of the antenna resulted in fields of 19 kV/m at the same distance, indicating a power gain of 7 dB and an ERP in excess of 1.5 GW.

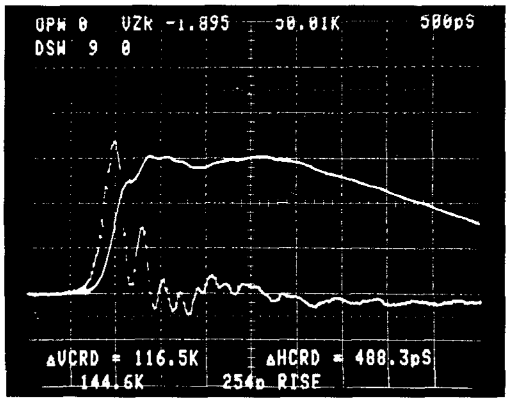

Figure 3. Derivative and integrated output waveforms of magnetic shock line. Measurement made via E-dot probe mounted on RG-177 coaxial cable.

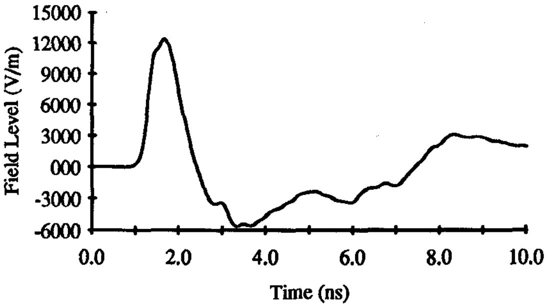

Figure 4. Integrated TEM field waveform. Measurement made via 3 GHz free-field D-dot probe.

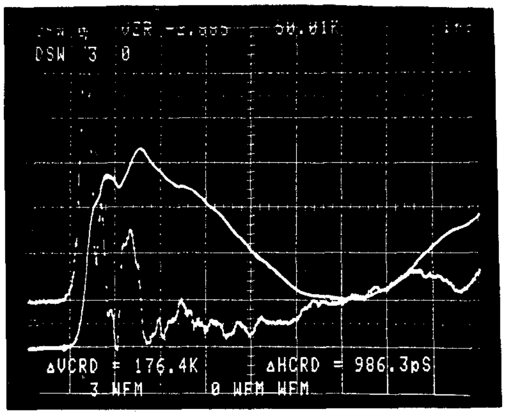

Figure 5. Derivative and integrated antenna waveforms. Derivative measurement made via 3 GHz ground plane D-dot probe.

SUMMARY

In summary, a highly advanced, all-solid state nonlinear magnetic pulse compressor has been developed. This system is highly reliable with a shot life in excess of 10^{11} shots. It produces 150 kV pulses with 4 ns pulse widths and rise times less than 200 ps. The overall efficiency of the system is approximately 12.5 percent. An important point to consider is the scalability of this technology to higher levels. A larger system under development has an input pulse energy of 25 joules and is projected to produce 500 kV pulses with the same parameters. Other higher energy modulators are already in use at various locations in this country and merely require the additional stages and shock line designs to be adapted to this application. However, it is the opinion of the authors that such efforts at this time are premature. Sufficient data to justify the increased complexity and demand for prime power has not been generated to date.

For this reason, continuing efforts are primarily focused on improving the efficiency of the present systems and on the design of higher gain, wide band antennas. The pulse widths to date are too long to be supported on the plates of the moderately large TEM horns (5 foot plates) currently in use. Furthermore, the clear time of these antennas are approximately 1 ns, which effectively chops off the remainder of the pulse produced on the antenna plates. By extending the compression limits of the system to produce pulse widths near 1 ns, increases in both the amplitude and in the radiation efficiency of the antenna will be achieved. The ERP of the antenna will be improved by increasing the gain of the antenna with narrower plate angles and longer plates.

Transportability, though not a significant problem at this time, is somewhat inconvenient, and a design is under way to house the entire system and its ancillary gear within a customized passenger-style cargo van. Lastly, the issue of prime power is being addressed by the design of a battery pack which will supply all necessary power and biasing to the modulator and which will itself be recharged by the van's alternator. A smaller, more aesthetic version of the modulator will use a single commutator module for an output of 75 kV and will require no external source of prime power. The expected run time of this system is equivalent to 2 hours of continuous run time at 5 kHz.

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