COMPLETELY EXPLOSIVE ULTRACOMPACT HIGH-VOLTAGE PULSE GENERATING SYSTEM

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ABSTARCT

A conventional pulsed power technology has been combined with an explosive pulsed power technology to produce an autonomous high voltage power supply. The power supply contained an explosive-driven high-voltage primary power source and a power-conditioning stage. Two types of ultracompact explosive primary power sources were used, one of which was based on the physical effect of shock wave demagnetization of high-energy ferromagnets, and the other one was based on shock wave depolarization of high-energy ferroelectric materials. The volumes of the energy-carrying ferroelectric elements in the shock wave ferroelectric generators (FEGs) varied from 1.2 to 2.6 cm^3. The volume of the energy-carrying ferromagnetic elements in the shock wave ferromagnetic generators (FMGs) was 8.75 cm^3 for all tests performed. The power-conditioning stage was based on the spiral vector inversion generator (VIG). The combined FEG-VIG and FMG-VIG systems demonstrated successful operation and good performance. The output voltage pulse amplitude of the combined FEG-VIG system exceeded 90 kV, with risetime of 6.8 ns.

I. INTRODUCTION

The development of autonomous compact pulsed power systems is important to the success of many scientific and engineering projects [1]. A novel type of autonomous explosive-driven pulsed power source, utilizing the electromagnetic energy stored for an infinite period of time in high-energy hard ferri- and ferromagnets, was developed recently [2-5]. Operation of these devices is based on the fundamental physical effects of shock wave demagnetization of hard ferri- [2] and ferromagnets [3-5]. Miniature (9 to 25 cm^3 in volume) generators are capable of producing high voltage pulses with amplitudes greater than 20 kV and pulses of high current with amplitudes exceeding 4 kA [6-8].

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Piezoelectrics and ferroelectrics are another class of materials capable of storing electromagnetic energy for an infinite period of time. The design and performance of recently developed autonomous pulsed power sources utilizing electromagnetic energy stored in ferroelectric materials are described in [9]. Compact explosive-driven generators based on shock wave depolarization of ferroelectric energy-carrying elements have been demonstrated to be reliable and have controllable electrical operation [9-11].

In this work we successfully combined explosive-driven shock wave ferroelectric generators and ferromagnetic generators with a pulsed transformer, the spiral vector inversion generator [12].

II. EXPERIMENTAL TECHNIQUE

Explosive experiments were performed at the Rock Mechanics and Explosive Research Center at the University of Missouri-Rolla where we designed and constructed the experimental system to study explosive-driven pulsed power and microwave sources. Our main guideline for the design and development of the experimental system was to use commercial probes for monitoring the pulsed power signals. Out of several possibilities, we chose the design shown in Fig. 1. The setup has a detonation tank where the explosive-driven generators are fired, and a diagnostic/test station.

The detonation tank is a cylindrical steel chamber of 3.5 m in diameter and 7 m in length having nominal 1-inch wall thickness. The tank is capable of withstanding non-fragmenting tests of up to 1 kg of high explosives. The explosive-driven generators tested are placed inside the detonation tank near a stainless steel side port. The diagnostic/test station containing probes, oscilloscopes and other diagnostic and experimental equipment is placed near the side port, outside of the detonation tank. Some of generator's output cables are connected to the diagnostic/test station through air sealed connectors in the port. Other generator's output cables are connected to the diagnostic/test station directly. In order to avoid mechanical strains being transmitted through the generator's output cables to the pulse measuring and

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14. ABSTRACT

A conventional pulsed power technology has been combined with an explosive pulsed power technology to produce an autonomous high voltage power supply. The power supply contained an explosive-driven high-voltage primary power source and a power-conditioning stage. Two types of ultracompact explosive primary power sources were used, one of which was based on the physical effect of shock wave demagnetization of highenergy ferromagnets, and the other one was based on shock wave depolarization of high-energy ferroelectric materials. The volumes of the energy-carrying ferroelectric elements in the shock wave ferroelectric generators (FEGs) varied from 1.2 to 2.6 cm3. The volume of the energy-carrying ferromagnetic elements in the shock wave ferromagnetic generators (FMGs) was 8.75 cm3 for all tests performed. The power-conditioning stage was based on the spiral vector inversion generator (VIG). The combined FEG-VIG and FMG-VIG systems demonstrated successful operation and good performance. The output voltage pulse amplitude of the combined FEGVIG system exceeded 90 kV, with risetime of 6.8 ns.

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recording systems during generator firing, the output cables are fixed in the port cover using specially developed cylindrical clamps. During generator explosive operation, the cables cut off at their generator connections instead of at the measuring system connections. Since mechanical strains are not transferred to the diagnostic/test station through the cables, there is no mechanical effect from the explosive detonation on the results of the electrical measurements. Positioning the sensitive equipment outside the tank in this manner protects the equipment from the explosive environment within the tank, thereby preventing test-related damage.
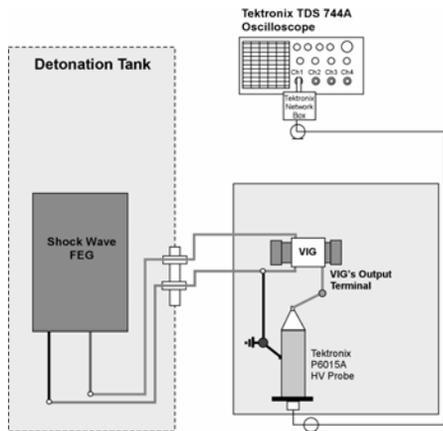
Figure 1. Schematic diagram of the experimental setup used to test the explosive FEG-VIG system.

III. EXPERIMENTAL RESULTS

A schematic diagram of an explosive-driven high-voltage FEG is shown is shown in Fig. 2. It contains a cylindrical body, an explosive chamber, an aluminum impactor, a holder containing the ferroelectric module (the energy-carrying element), and a load circuit. All the generators used in these experiments were charged with 14 g of desensitized RDX and the explosive was initiated by a RISI RP-501 exploding bridgewire detonator. Detailed information about the design of the shock wave FEG can be found in [9].

The first series of experiments was performed with FEGs containing poled lead zirconate titanate (PZT) $Pb(Zr_{52}Ti_{48})O_3$ polycrystalline ceramic disks (supplied by EDO Corp.) of diameter $D = 27$ mm and thickness $h = 2.1$ mm. The waveform of a typical electromotive force (EMF) pulse produced by an FEG operating in the open circuit mode is shown in Fig. 3. The EMF pulse amplitude was $U_g(t)_{max} = 6.88$ kV, the full width at half maximum (FWHM) was 0.68 μs, and the risetime was $\tau = 0.81$ μs.

The VIG chosen for the first experiments was an 8-turn units made with 4 mil (thickness) capacitor grade Teflon as the dielectric and 2 inch wide, 2 mil copper shims as the capacitor conducting plates. These VIGs were wound on ferrimagnetic mandrels (ferrite 2535) with a width of 1 inch. This produced a "rectangular cross section" for the

VIG but did not affect its efficiency. The voltage efficiency (measured by voltage multiplication) of the devices was in the 80- 90% range. The calculated capacitance of the devices was approximately 8.9 nF. Typical VIGs are shown in Figure 4.
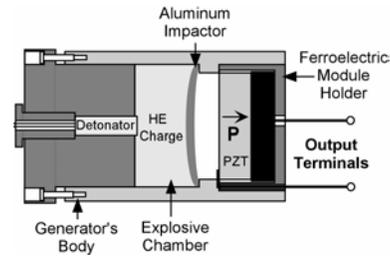
Figure 2. Schematic diagram of an explosive-driven shock wave ferroelectric generator.
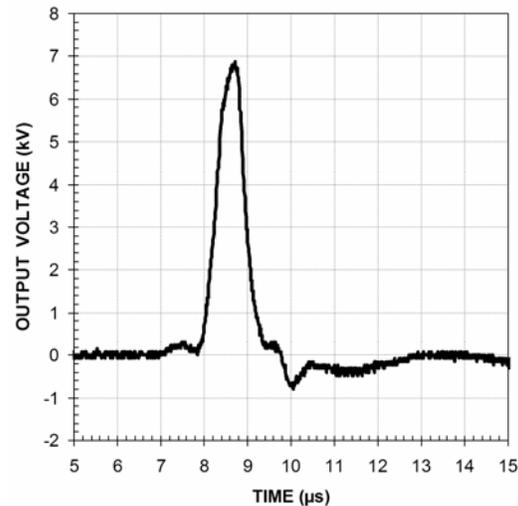
Figure 3. Waveform of the pulsed electromotive force produced by an FEG. Open circuit operation. PZT energy-carrying element of $D = 27$ mm/$h = 2.1$ mm.

The development of a VIG spark gap is mostly a matter of trial and error. A standard paper punch was used to make a repeatable hole in dielectric films which could be stacked to lengthen the gap. In this way, the switch inductance was kept at a minimum and the breakdown voltage could be somewhat controlled. To get some idea of the impulse behavior of the gap, we developed a simple test fixture to allow an impulse to be applied to the switch ensemble.

A schematic diagram of the experimental setup used to test the FEG-VIG system is shown in Fig. 1. The FEG was placed inside the detonation tank. The output terminals of the FEG were connected to the input of the VIG. The negative terminal of the FEG was grounded. Correspondingly, the FEG produced a positive high-voltage pulse. This high-voltage pulse was applied to the input of the VIG spark gap. The output voltage of completely explosive FEG-VIG system was monitored by a commercial high voltage probe (Tektronix P6015A) that was connected directly to the output of the VIG.
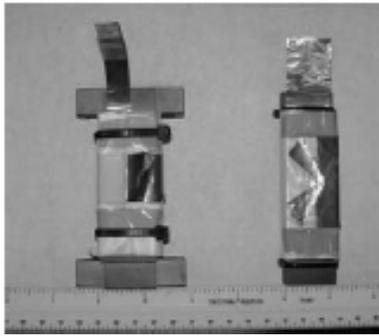
Figure 4. Photo of VIGs used in this experimental series.

Operation of the FEG-VIG system is as follows. The explosive-driven FEG produces a microsecond pulse that impulse charges the VIG. When the charge voltage exceeds the VIG spark gap hold off threshold, the VIG erects in a time equal to two wave transit times through the device (~6ns), producing a transient voltage that is several times greater than the breakdown voltage of the VIG spark gap switch. Preliminary characterization of the VIG spark gap was done in the laboratory in real time, and the gap was tuned using a high voltage D.C. power supply and was set to break at approximately 3 kV.
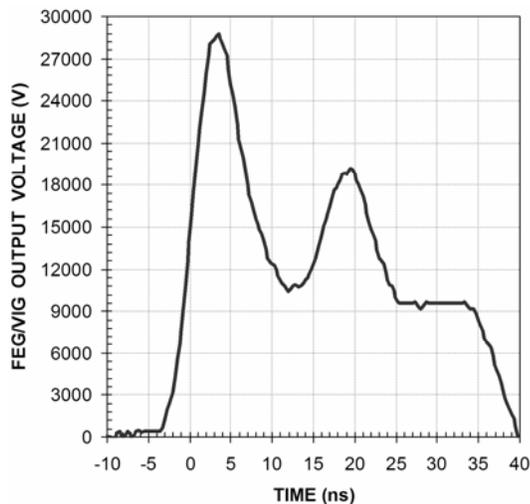
Figure 5. The waveform of a typical high-voltage pulse produced by an explosive-driven FEG-VIG system. The FEG contained the PZT disk of $D = 27$ mm/$h = 2.1$ mm. The VIG spark gap breakdown voltage was 2.6 kV.

The waveform of a typical high-voltage pulse produced by an FEG-VIG system is shown in Fig. 5. The peak voltage amplitude was $U(t)_{max} = 28.8$ kV, FWHM = 20 ns and the risetime was $\tau = 6.75$ ns. The actual VIG charge voltage at the gap trigger point can be calculated from the spiral efficiency and the output voltage. The unit triggered at about 2.6 kV. Even at only 28.8 kV the effects of corona in the VIG are appreciable and reduced the efficiency of the system to approximately 75%.

The next series of tests was performed with FEGs containing PZT disks of dimensions $D = 25$ mm/$h = 5.1$

mm. The pulsed EMF waveform produced by an FEG operating in the open circuit mode is shown in Fig. 6. The EMF pulse amplitude was $U_g(t)_{max} = 17.1$ kV, FWHM = 0.89 μs and $\tau = 1.2$ μs.
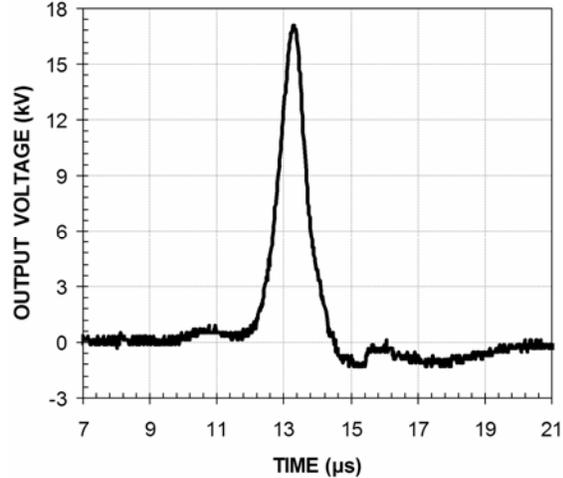
Figure 6. Waveform of the pulsed electromotive force produced by an FEG. Open circuit operation. PZT energy-carrying element dimensions were $D = 25$mm/$h = 5.1$ mm.

In this series of experiments, we used a 5-turn VIG. The device was prepared similarly to the 8-turn unit (see description above), but was oil impregnated to eliminate corona effects and capable of producing output voltages in excess of 100 kV. The calculated capacitance of the VIG was on the order of 5.6 nF. The breakdown voltage of the VIG spark gap was once again tuned to trigger at a set voltage using a high voltage D.C. power supply to ensure that the unit would discharge at the appropriate time. The spark gap spacing was set to DC discharge at approximately 6 kV, expecting that it would probably be more than that under impulse conditions. The experimental setup for this series of tests was similar to that in the previous series (Fig. 1). The only difference was that we used a custom voltage divider with a coefficient of 5.02 connected to the Tektronix P6015A high-voltage probe.

The waveform of a typical high-voltage pulse produced by an FEG-VIG system is shown in Fig. 7. The peak voltage amplitude was $U(t)_{max} = 91.4$ kV, FWHM = 6.5 ns and $\tau = 5.25$ ns. The risetime of the pulse is approaching the resolution limit of the Tektronix high voltage probe. Probe resolution, as well as stray capacitive effects, may distort the rise time for FEG-VIG systems and introduce considerable risetime error. The calculated rise time for this system was on the order of 4 ns. The unit triggered at approximately 11.1 kilovolts, which is almost twice the level at which the spark gap switch was set to break under DC conditions.

The next series of experiments was performed with FMG-VIG systems. The shock wave FMG consisted of a hollow, hard ferromagnetic cylindrical $Nd_2Fe_{14}B$ energy-carrying element ($D = 25.4$ mm/$h = 19$ mm, unit volume

8.75 cm^3), a pulse-generating coil holder, and a multi-turn pulse generating coil. All of the generators used in these experiments were loaded with 0.6 g of desensitized RDX and initiated by a single RP-501 [3-6].
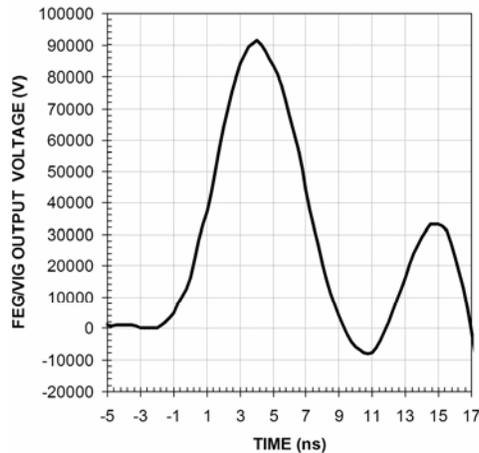
Figure 7. The waveform of a typical high-voltage pulse produced by explosive-driven FEG/VIG system. The FEG contained a PZT disk of $D = 25$ mm/$h = 5.1$ mm. The VIG spark gap breakdown voltage was 11.1 kV.

The EMF waveform produced by a typical FMG containing a 257-turn pulse-generating coil operating in the open circuit mode is shown in Fig. 8. The EMF pulse amplitude was $U_g(t)_{max} = 9.44$ kV, FWHM = 6.67 μs and $\tau = 2.7$ μs. The series resistance and the series inductance of the pulse-generating coil were R_S(100 kHz) = 15.1 Ω and L_S(100 KHz) = 2.33 mH, respectively.

The experimental setup for FMG-VIG experiments was similar to that for the FEG-VIG tests, and utilized an oil impregnated VIG. The waveform of a high-voltage pulse produced by an explosive-driven FMG-VIG system is shown in Fig. 9. The peak voltage amplitude was $U(t)_{max}$ = 40.2 kV, FWHM = 14 ns and $\tau = 7.5$ ns. The waveform of the pulse is different from that obtained for the FEG-VIG system (Fig. 7) and the amplitude of the pulse is lower. A possible reason for this is in the inductive nature of the FMG pulse-generating system.

III. SUMMARY

We have demonstrated successful operation for the first time of completely explosive pulsed power systems based on explosive FEGs and FMGs as the primary power sources with a VIG as a power conditioning stage. Adding a VIG stage increases the voltage output of the FEG and FMG by a factor depending on the VIG's parameters, while simultaneously compressing the pulse into the range of a few nanoseconds. The combination produces an extremely high power, dense, single-shot pulser that is unrivaled for specific power.
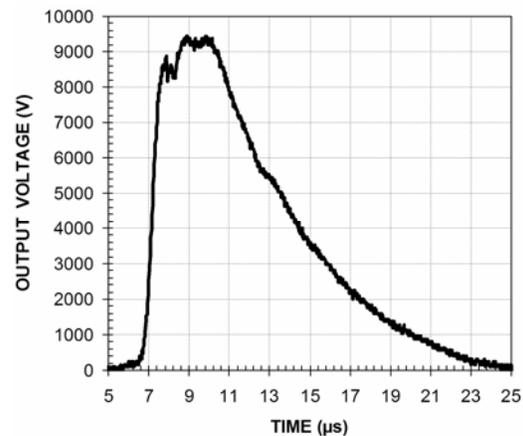
Figure 8. Waveform of the pulsed electromotive force produced by an FMG (257-turn pulse-generating coil). Open circuit operation.
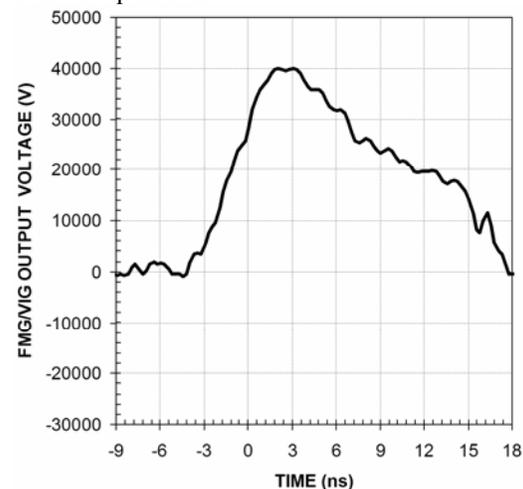
Figure 9. The waveform of the high-voltage pulse produced by an explosive-driven FMG-VIG system.

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