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Sergey I. Shkuratov

Evgueni F. Talantsev

Jason Baird
Missouri University of Science and Technology, jbaird@mst.edu

Allen H. Stults

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/min_nuceng_facwork/1176

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PULSE CHARGING OF CAPACITOR BANK BY EXPLOSIVE-DRIVEN SHOCK WAVE FERROELECTRIC GENERATOR

Sergey I. Shkuratov, Loki Incorporated, Rolla, MO 65409, U.S.A
Evgueni F. Talantsev, Loki Incorporated, Rolla, MO 65409, U.S.A
Jason Baird, Loki Incorporated, Rolla, MO 65409, U.S.A
Larry L. Altgilbers, U.S. Army Space and Missile Defense Command, Huntsville, AL 35807, U.S.A.
Allen H. Stults, U.S. Army Research, Development and Engineering Command, Huntsville, AL 35898, U.S.A.

ABSTRACT

Ultracompact explosive-driven shock wave ferroelelectric generators (FEGs) were used as autonomous primary power sources for charging capacitor banks of different capacitance. The FEGs utilized longitudinal (when the shock wave propagates along the polarization vector **P**) shock wave depolarization of $Pb(Zr_{52}Ti_{48})O_3$ (PZT) polycrystalline ferroelectric ceramic. PZT disks having diameters ranging from 25 to 27 mm and three different thicknesses: 0.65, 2.1, and 5.1 mm. It was experimentally shown that during the charging process the FEGs were capable of producing pulsed power with peak amplitudes up to 0.3 MW. Results for charging voltage, electric charge transfer and energy transfer from the FEGs to the capacitor banks of capacitances C_L = 2.25, 4.5, 9.0, 18.0, and 36.0 nF are presented. Analysis of the experimental data shows that the maximum energy transfer from the FEG to the capacitor bank differs for each type of ferroelectric energy-carrying element, and is dependent upon the capacitance of the capacitor banks.

INTRODUCTION

One of the common pulsed power generator designs is based on the utilization of capacitors as energy storage units [1]. In these generators, electric energy is provided to the capacitive energy storage by high-voltage power sources powered by a conventional 110/220 V - 50/60 Hz supply line. Recently, the tendency in development of pulsed power systems is to make these systems autonomous and, in certain applications, explosive-driven.

The authors achieved significant progress in this approach in recent months. In [2], we demonstrated successful operation of an autonomous two-stage pulsed power system containing capacitive energy storage and a recently invented [3-8] high-voltage explosive-driven ferromagnetic generator (FMG) as the primary power source. FMGs utilize the electromagnetic energy stored for infinite periods in high-energy hard ferromagnets [3-8]. Operation of these devices is based on the fundamental physical effects of longitudinal [3-4] and transverse [5-8] shock wave demagnetization of hard ferri- and ferromagnets.

Other sources of electromagnetic energy that store energy for infinite periods of time in a solid state are piezo- and ferroelectrics. Recently, we developed a series of compact autonomous explosive-driven generators utilizing the electromagnetic energy stored in ferroelectric materials [9]. We named these devices shock-wave ferroelectric generators (FEGs), and their operation [9] is based on the effect of longitudinal shock wave depolarization of $Pb(Zr_{52}Ti_{48})O_3$ ferroelectrics [10].

In the last few months, we successfully combined our explosive-driven longitudinal FEGs [9,10] with a conventional non-explosive nanosecond power-conditioning device [the spiral vector inversion generator, or VIG] [11]. We have demonstrated that an autonomous FEG-VIG pulsed power system is capable of generating output voltage pulses with amplitudes that exceed 90 kV with a rise time of 5 ns [11].

In this paper, we present results of the systematic investigation of an autonomous two-stage pulsed power system based on using a longitudinal shock wave FEG as the charging source for capacitive energy storage elements (a capacitor bank).

EXPERIMENTAL TECHNIQUE

The authors performed the explosive experiments discussed herein at the Rock Mechanics and Explosive Research Center at the University of Missouri-Rolla. Figure 1 shows a schematic diagram of the longitudinal shock wave FEG and explosive experiment setup. The FEGs contained a cylindrical body, an explosive chamber, a metallic impactor (flyer plate), and a ferroelectric module. The bodies and explosive chambers of the FEGs were made of polycarbonate. All the generators were loaded with 14 g of desensitized RDX and initiated by a single RISI RP-501 exploding bridgewire (EBW) detonator. A detailed description of the FEG can be found in [9,10].

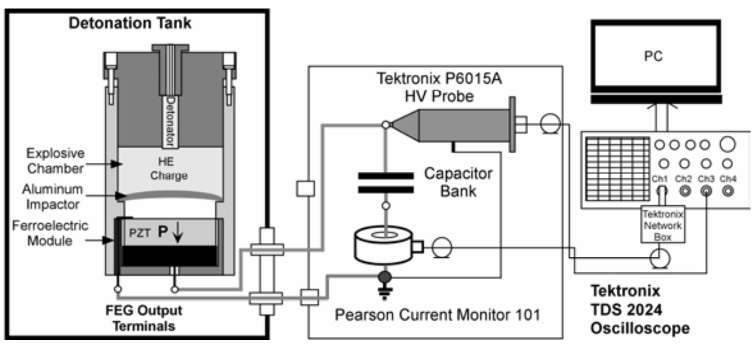


Figure 1. Schematic diagram of an explosive-driven longitudinal shock wave ferroelectric generator and measuring circuit for investigating the operation of FEG-Capacitor bank systems.

The energy-carrying elements in the generators were poled lead zirconate titanate (PZT) $Pb(Zr_{52}Ti_{48})O_3$ polycrystalline piezoelectric ceramic disks (supplied by EDO Corp.) of several sizes – diameter D = 27 mm/length h = 0.65 mm, D = 25 mm/h = 2.1 mm, and D = 25 mm/h = 5.1 mm. The parameters of the $Pb(Zr_{52}Ti_{48})O_3$ are: density $7.5 \cdot 10^3$ kg/m^3, dielectric constant 1300, Curie temperature 320° C, Young's modulus $7.8 \cdot 10^{10}$ N/m^2, piezoelectric constant $d_{33} = 295 \cdot 10^{-12}$ C/N, piezoelectric constant $g_{33} = 25 \cdot 10^{-3}$ m^2/C, and remnant polarization P_0 = 30 μC/cm^2.

The capacitor banks were made of 1.8 nF ceramic capacitors, with nominal voltages of 6.0 kV that were combined into capacitor modules. Each capacitor module combined five ceramic capacitors and was attached to two cylindrical plastic stands bolted to the bottom of the measuring box. Each capacitor bank placed in the measuring box contained a certain number of capacitor modules connected in series or in parallel.

RESULTS AND DISCUSSION

Before studying the operation of FEG-Capacitor bank systems, we performed a series of investigations with FEGs operating in the open circuit mode [9-12]. Waveforms and amplitudes of electromotive force pulses [EMF, E_g(t)] produced by the FEGs were highly reproducible. It follows from our results that the amplitude of the EMF pulses was directly proportional to the thickness of the $Pb(Zr_{52}Ti_{48})O_3$ disks. The slope of the amplitude plot versus thicknesses of the $Pb(Zr_{52}Ti_{48})O_3$ disks was $E_b = \Delta E_g(t)_{max}/h = 3.3$ kV/mm [9,12].

In the charging mode, the EMF pulse generated by the PZT module due to shock wave depolarization caused a pulsed electric current, $I(t)$, to flow in the FEG-capacitor bank electrical circuit. In these experiments, we did not use high-voltage diodes or high-voltage rectifiers. The high voltage output terminal of the FEG was connected directly to the high-voltage terminal of the capacitor bank and to a Tektronix P6015A high-voltage probe. The negative plate of PZT disk was connected to the ground terminal of the capacitor bank through a Pearson Current Monitor (model 101).

Integration of the charging current, $I(t)$, waveform from 0 to t gives the momentary value of the electric charge, ΔQ(t), transferred to the capacitor bank during explosive operation of the FEG:

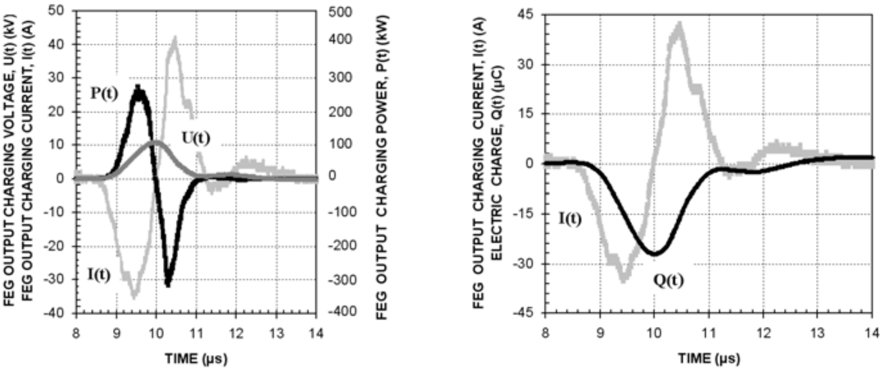
$$\Delta Q(t) = \int_0^t I(t)\cdot dt \qquad (1)$$

We performed FEG-Capacitor bank experiments over a wide range of load capacitances, from C_L = 2.25 nF to C_L = 36 nF. Figure 2(a) shows the results of a typical experiment for pulsed charging of a 2.25 nF capacitor bank by an FEG containing a $Pb(Zr_{52}Ti_{48})O_3$ disk of D = 25 mm/h = 5.1 mm. The peak voltage amplitude [Fig. 2(a)] of the charging pulse was $U(t)_{max}$ = 10.98 kV, the FWHM of the pulse was 1.2 μs, and τ = 1.25 μs. The slope of the $U(t)$ curve at the moment depolarization began was $\Delta U(t)/\Delta t$ = 8.8 kV/μs.

The increase in the charging voltage pulse from zero to its peak value in Fig. 2(a) was the direct result of the depolarization of the ferroelectric energy-carrying element due to the shock wave action. Electric charge, induced as a result of the shock wave depolarization of the ferroelectric module, was released on the contact plates of the PZT disk and it was utilized to charge the PZT element itself (it is initially a capacitor) to a high voltage. The electric charge was then transferred to the external circuit to charge a capacitor bank.

After reaching its maximum value, the high-voltage pulse decreased to zero in 1.0 μs [see Fig. 2(a)]. Therefore, the right edge of the output voltage pulse, U(t), is 20% shorter than left edge. Apparently, the decrease in the pulse after reaching its peak value was the result of significant increases in the electrical conductivity of the shock-compressed PZT ceramic material (and the corresponding leakage current in the element), or to internal electrical breakdown within the ceramic disk.

The peak energy delivered to the capacitor bank (capacitance, C_L = 2.25 nF) reached a value of $W(t)_{max} = C_{0L}\ U(t)_{max}^2/2$ = 136 mJ. The average amplitude (determined from 4 experiments) of the charging voltage pulse was $U(t)_{max\ ave}$ =10.7 ± 2.4 kV.



(a) (b)

Figure 2. Typical waveforms of the output charging voltage, $U(t)$, current, $I(t)$, circulation of electric charge, $\Delta Q(t)$, and power, $P(t)$, produced by the FEG containing a $Pb(Zr_{52}Ti_{48})O_3$ disk of D = 25 mm/h = 5.1 mm across a 2.25 nF capacitor bank. a - waveforms of the high voltage pulse, $U(t)$ (dark gray), charging current, $I(t)$ (light gray), and power delivered to the capacitor bank, $P(t)$ (black); b - waveforms of the charging current, $I(t)$, (gray) and circulation of electric charge in the circuit, $\Delta Q(t)$ (black).

The power dissipated in the load, $P(t)$, was determined by finding the product of the instantaneous value of the output voltage $U(t)$ and the instantaneous current in the circuit, $I(t)$: $P(t) = I(t)\cdot U(t)$. The peak FEG output charging power reached $P(t)_{max}$ = 0.27 MW.

Figure 2(b) shows the simultaneous waveforms of the charging current, $I(t)$, in the circuit and the circulation of electric charge. The peak amplitude of the negative (charging) current pulse was $I_1(t)_{max}$ = -35.6 A, the FWHM was 0.87 μs and τ = 0.8 μs. Therefore, the ΔQ_{max} transferred from the PZT module to the capacitor bank during explosive operation of the FEG was 27 μC.

Figures 3 and 4 summarize experimental results that we obtained for all explosive-driven FEG-Capacitor bank systems that we investigated. Figure 3 shows the high-voltage pulse amplitudes produced by FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 27 mm/h = 0.65 mm, D = 25 mm/h = 2.1 mm, and D = 25 mm/h = 5.1 mm across capacitor banks of different capacitances, from C_L = 2.25 nF to C_L = 36 nF. It follows from the experimental results that increasing the capacitance of the bank leads to a gradual decrease in the high-voltage produced by the FEGs containing all three types of ferroelectric energy-carrying elements. The highest voltage, U_{max} = 13.7 kV, was obtained across a 2.25 nF capacitor bank charged by the FEG containing a $Pb(Zr_{52}Ti_{48})O_3$ disk of D = 23 mm/h = 5.1 mm.

Figure 4(a) shows the electric charge transferred from FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 27 mm/h = 0.65 mm, D = 25 mm/h = 2.1 mm, and D = 25 mm/h = 5.1 mm to the capacitor banks. The charge transfer strongly depends on the capacitance of the capacitor bank. Increased capacitance results in a significant increase in the electric charge transferred from the ferroelectric energy-carrying elements. The maximum electric charge was transferred from $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 27 mm/h = 0.65 mm to a 36 nF capacitor bank, Q_{max} = 72 μC.

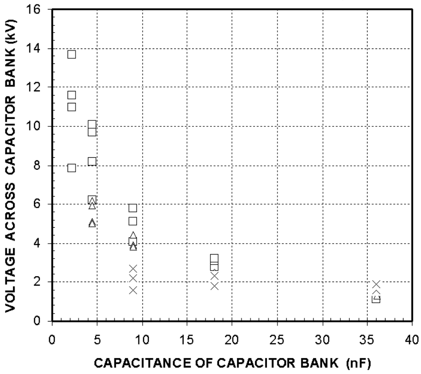


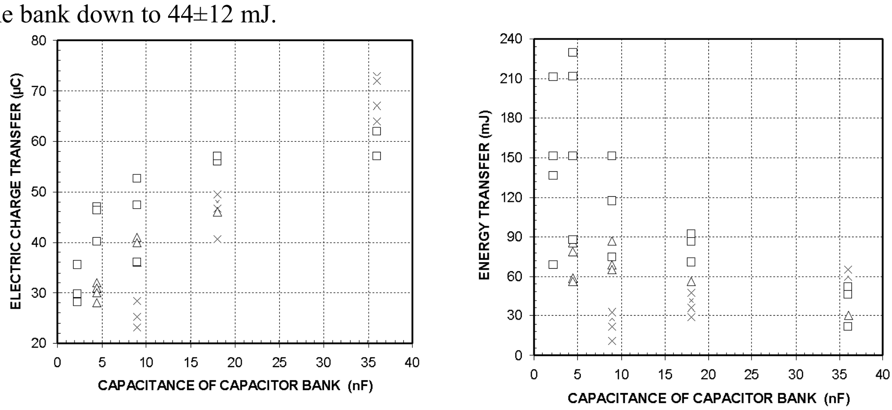
Figure 3. Amplitude of the voltage pulse produced by FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disk with D = 27 mm/h = 0.65 mm (crosses), D = 25 mm/h = 2.1 mm (triangles) and D = 25 mm/h = 5.1 mm (squares) across capacitor banks of different capacitance.

Figure 4(b) shows the energy delivered from the FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 27 mm/h = 0.65 mm, D = 25 mm/h = 2.1 mm, and D = 25 mm/h = 5.1 mm to the capacitor banks. It can be seen that the behavior of the energy transfer is very different for different types of ferroelectric energy-carrying elements and bank capacitances.

For FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 27 mm/h = 0.65 mm, an increase of the capacitance of the bank from 9 to 36 nF results in a significant increase in the energy transfer, from 17±6 mJ to 52±12 mJ.

For FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 25 mm/h = 2.1 mm, an increase of the capacitance of the bank from 4.5 to 9 nF results in an increase in the energy transfer from 68±12 mJ to 79±9 mJ. Further increases of the capacitance of the bank from 9 to 36 nF, however, results in a gradual decrease of the energy transfer down to 30 mJ.

For FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disks of D = 25 mm/h = 5.1 mm, an increase of the capacitance of the bank from 2.25 to 4.5 nF results in increase in the energy transfer, from 133±27 mJ to 168±24 mJ. Further increasing the capacitance of the bank from 4.5 to 36 nF results in a gradual decrease of the energy transfer from ferroelectric module to the bank down to 44±12 mJ.



(a) (b)

Figure 4. Electric charge (a) and energy (b) transferred from FEGs containing $Pb(Zr_{52}Ti_{48})O_3$ disk with D = 27 mm/h = 0.65 mm (crosses), D = 25 mm/h = 2.1 mm (triangles) and D = 25 mm/h = 5.1 mm (squares) to capacitor banks of different capacitance.

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