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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/1190

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NEW CONCEPT FOR CONSTRUCTING AN AUTONOMOUS COMPLETELY EXPLOSIVE PULSED POWER SYSTEM: TRANSVERSE SHOCK WAVE FERROMAGNETIC PRIMARY POWER SOURCE AND LOOP FLUX COMPRESSION AMPLIFIER

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

A new design idea for a compact, autonomous, completely explosive pulsed power system is proposed. The system is based on the shock wave ferromagnetic generator (FMG) as a primary power source and a loop magnetic flux compression generator (LFCG) as a pulsed power amplifier. The FMG primary power source utilizes the effect of transverse shock wave demagnetization of $Nd_2Fe_{14}B$ high-energy hard ferromagnets to produce the seed current. Results are presented of an experimental study and digital simulation of operation of the FMG-LFCG system.

INTRODUCTION

Scientific and engineering activity in the field of compact explosive pulsed power generation has increased for the past few years. One result of our previous efforts in this field was the invention a new type of explosive-driven primary power source that we call a shock-wave ferromagnetic generator (FMG) [1-6]. This device does not utilize magnetic flux compression (via the magnetic cumulation effect), but it is based on the physical effects of longitudinal [1, 2] and transverse [3-7] shock wave demagnetization of hard ferrimagnets and hard ferromagnets.

There are two different approaches to the application of FMGs in explosive pulsed power. The first approach is based on the idea that FMGs can be used as autonomous explosive-driven primary sources for powering conventional non-explosive pulsed power systems. We developed the first approach, showing the feasibility of using FMGs as charging sources for Arkadiev-Marx generators [8]. Using the first approach, we also developed a new autonomous high-voltage nanosecond system [9]. This system utilizes a spiral vector inversion generator (VIG) as a power conditioning stage for an FMG. The miniature FMG-VIG system generated high-voltage pulses with amplitudes exceeding 40 kV and rise times in the range of 5-8 ns.

The second approach for FMG application is to use it as a primary power source for explosive-driven devices that require seed currents. To develop the second approach, we experimentally demonstrated the successful operation of a completely explosive pulsed power system utilizing a multi-turn transverse shock wave FMG as the seed source and a helical FCG as a pulsed power amplifier [10, 11].

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In this paper, we propose a new concept under the second approach for constructing completely explosive pulsed power systems and discuss the first results obtained from our investigation of the concept. It utilizes a high-current transverse shock wave FMG as the primary power source and a miniature loop magnetic flux compression generator (LFCG) [12, 13] as a pulsed power amplifier.

MINI-LFCG DESIGN

The LFCG was invented about 10 years ago [12, 13], but not much information about them is available in open sources. We started our R&D work on the LFCG practically from zero because the two referenced papers do not contain technical details. Moreover, our task was to develop miniature, completely explosive pulsed power systems with FMG seed sources. This is a completely new approach to the design of systems of this type, because the systems described in the publications are large LFCGs powered from conventionally charged capacitor seed sources.

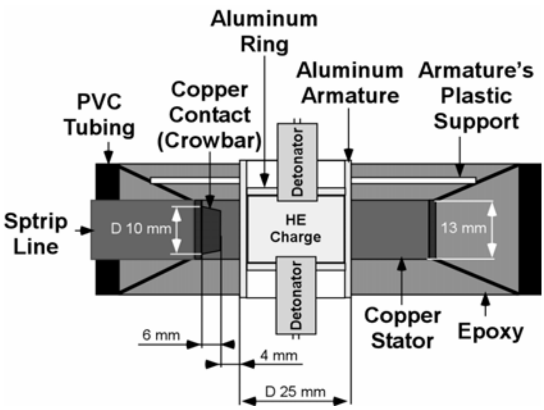


Figure 1. Schematic diagram of mini-LFCG.

A schematic diagram of the LFCG design developed in this work is in Fig. 1. The stator of the LFCG was made of copper strip of 1 mm thickness and 13 mm width. The diameter of the stator was 50 mm, and we insulated it with three layers of Kapton™ tape. We encapsulated the external part of the stator along its perimeter with a high-strength epoxy and PVC pipe in order to keep the stator in place during explosive operation of the device.

Two copper cylindrical contacts of the crowbar were bolted and soldered to the stator of the generators from both sides of the input strip line (Figs. 1 and 2). The diameter and height of each contact were 10 mm and 6 mm, respectively. They had slightly conical shapes, and the distance between contacts was about 2 mm. We insulated their side surfaces with Kapton™ tape to avoid electrical breakdown during operation of the system.

We used cylindrical aluminum armatures of 25 mm diameter and 30 mm length. The explosive charge (11 or 12 g of desensitized RDX) was loaded in the central part of the armature, with a total charge length of 13 mm. We utilized two metallic detonator holders to hold two RISI RP-80 exploding bridge-wire (EBW) detonators at each end of the HE charge.

By design, we placed the armature off-center within the stator, with the displacement towards the copper contacts of the crowbar (Figs. 1 and 2). The distance between the armature and the crowbar contacts was 4 mm. A circular support made of 2 mm polycarbonate plate held the armature in position within the LFCG. The plate had a number of holes through it to weaken it in order to avoid restrictions on the armature expansion.

DESIGN OF COMPLETELY EXPLOSIVE FMG-LFCG SYSTEM

A three-dimensional schematic diagram of the FMG-LFCG system we developed in this work is in Fig. 2. It contains an explosive-driven FMG seed source, an LFCG, and a load loop. We connected the FMG seed source to the LFCG by a 38 mm-long strip transmission line, which we also used for connection of the LFCG to the load loop (where the current monitor was placed).

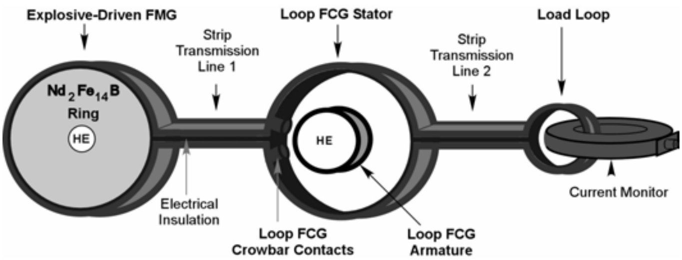


Figure 2. Schematic diagram of the completely explosive FMG-LFCG pulsed power mini-system developed in this work.

The $Nd_2Fe_{14}B$ hard ferromagnetic energy-carrying element of the FMG seed source (Fig. 2) was a hollow cylinder magnetized along its axis [6-11]. The dimensions of the $Nd_2Fe_{14}B$ energy-carrying element (volume of 25.1 cm^3) were as follows: outer diameter 50 mm, inner diameter 8 mm, and thickness 12.7 mm. The magnetic parameters of the $Nd_2Fe_{14}B$ were: residual flux density 1.23 T, coercive force 8.99 10^5 A/m, and maximum energy product 0.279 J/cm^3.

We loaded the high explosive charge for the FMG into the central hole along the axis of the $Nd_2Fe_{14}B$ hard ferromagnet. Detonation of the explosive initiated a transverse shock wave (the shock wave propagated perpendicular to the magnetization vector $\boldsymbol{M}$) in the body of the ferromagnetic energy-carrying element. In this FMG design (Fig. 2), we used a single RISI RP-501 EBW detonator along with 0.6 g of desensitized RDX.

We constructed the pulse-generating coil of the FMG seed source as a single coaxial turn of 13 mm width and 1 mm thickness. Two of the advantages of the single-coaxial-turn design of high-current FMGs developed in [7-11] are the extremely low internal inductance and resistance of the system [10-11], which are very important conditions for matching stages in the completely explosive FMG-LFCG system because of the low inductance and resistance of the LFCG. We insulated the perimeter of the $Nd_2Fe_{14}B$ hard ferromagnet [Fig. 2(b)] with three layers of vinyl tape.

RESULTS AND DISCUSSION

The basis of operation of the FMG seed source (Figs. 2 and 3) is the fundamental effect of transverse shock wave demagnetization of $Nd_2Fe_{14}B$ hard ferromagnets [6-11]. In accordance with Faraday's law, the decrease of initial magnetic flux in the FMG due to the transverse-shock-wave compression of the $Nd_2Fe_{14}B$ results in generation of a pulsed electromotive force [EMF, $E_g(t)$] at the output terminals of the single-turn pulse-generating coil. This EMF is applied to the input terminals of the LFCG and causes current flow in the FMG – LFCG – load circuit. For a single-turn coil, the generated EMF is

$$E_g(t) = - d\Phi(t)/dt, \qquad (1)$$

where dt is the time in which the change in the magnetic flux ($d\Phi(t)$) has taken place.

Before the explosive tests we performed a series of digital simulations of seeding processes. The methodology of simulation of the explosive-driven FMG seed source was developed in [10-11]. The equivalent circuit of the FMG-LFCG-Load system is in Fig. 3. It contains a pulsed electromotive force EMF; an inductance, L_{FMG}, and resistance, R_{FMG}, of the FMG (includes inductance and resistance of the strip transmission line connecting the FMG and the LFCG); a closing switch (crowbar); an inductance L_{LFCG}, and resistance, R_{LFCG}, of the LFCG; an inductance, L_{Load}, and resistance, R_{Load}, of the load loop (includes inductance and resistance of the strip transmission line connecting the LFCG and the load loop).

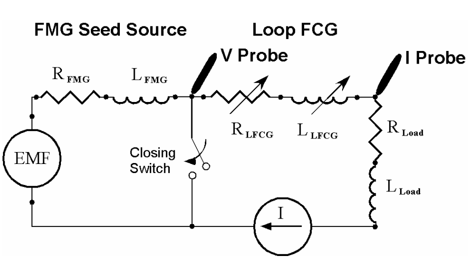


Figure 3. Equivalent circuit of the FMG-LFCG system.

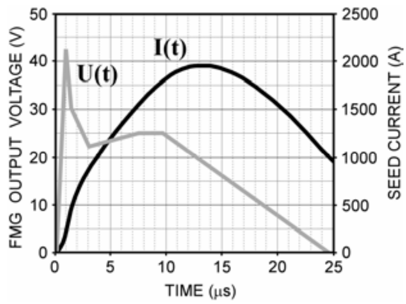
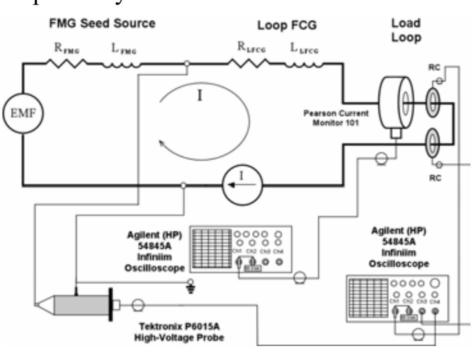


Figure 4. Digitally calculated waveforms of the seed current produced by explosive-driven FMG (black) and voltage across the LFCG-Load circuit (grey).

In this set of digital experiments we did not activate the closing switch and kept the inductance and the resistance of the LFCG constant during operation of the FMG seed source. The voltage and current probes are shown in Fig. 4 as V Probe and I Probe, respectively.



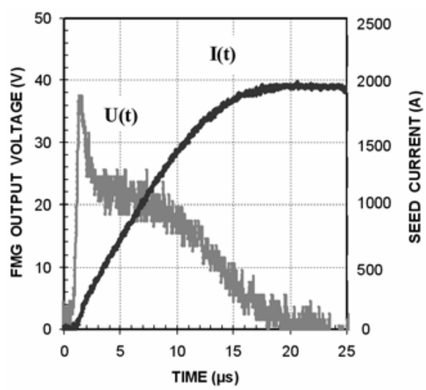


Figure 5. Schematic diagram of the measuring circuit for calibration of the seed current in the FMG-LFCG-load system.

Figure 6. Typical waveforms of the seed current produced by explosive-driven FMG (black) and voltage across the LFCG-Load circuit (grey).

Results of the digital experiments are in Fig. 4. The amplitude of the seed current produced by the FMG in the FMG-LFCG-Load circuit was 1.92 kA with the rise time, τ, of 13.6 μs. The amplitude of the voltage pulse across the LFCG-Load circuit was 46 V, with τ = 1.0 μs, and full wave at half maximum (FWHM) of 12.4 μs. Circuit parameters in this digital experiment were as following: L_{FMG} = 32 nH, R_{FMG} = 6.5 mΩ, L_{LFCG} = 52 nH, R_{LFCG} = 5.0 mΩ, L_{Load} = 42 nH, R_{Load}, = 4.5 mΩ.

A schematic diagram of the experimental setup for investigating seeding processes in the FMG-LFCG system is in Fig. 5. In first few experiments, an explosive charge was not loaded in the LFCG cylindrical armature, but was loaded in the FMG seed source only. The main goal of these tests was to get detailed information about the seed current pulse in the FMG-LFCG system. The LFCG armature should close the closing switch at the moment in time when the seed current is close to its maximum. Thus, we had to study the parameters of the seed current pulse [amplitude, duration (FWHM), rise time, etc.].

Typical experimental waveforms of the seed current pulse and the voltage across the LFCG-Load circuit are in Fig. 6. The amplitude of the current was 1980 A, with τ = 16.4 μs. The parameters of the seed current pulses were very close in each of the three experiments we performed, $I(t)_{seed\ aver}$ = 1930 ± 60 A. The amplitude of the voltage was 37.5 V, τ = 0.98 μs, and FWHM = 10.6 μs.

Comparing the rise time and the amplitude of the seed current and voltage obtained in the experiments (Fig. 6) and in the digital simulation (Fig. 4) allows one to conclude there was good agreement between the predicted and experimental results.

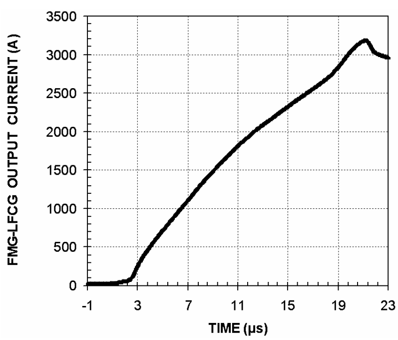


Figure 7. Typical waveform of the current produced by the completely explosive FMG-LFCG-Load loop system.

Next, we proceeded to all-up testing. The system operated as follows. The transverse shock wave in the $Nd_2Fe_{14}B$ energy-carrying element of the FMG produced a seed current pulse in the FMG-LFCG system. When the seed current was close to maximum, we sent the initiation pulse for the detonators of the LFCG. After initiation of the explosive charge in the armature of the LFCG, the armature expanded toward the LFCG stator. During the expansion, the armature closed two copper contacts in the LFCG stator (Figs. 1 and 2). When the contacts closed, the FMG seed source disconnected from the LFCG and the current in the stator of the LFCG and in the load loop seeded by the FMG started increasing due to the magnetic flux compression effect within the LFCG.

A typical waveform of the current pulse produced by the FMG-LFCG system is in Fig. 7. The amplitude of the current pulse reached 3170 A at 21 μs. Therefore, the current gain was 1.6.

CONCLUSION

We proposed and studied an autonomous, completely explosive-driven pulsed power system based on an ultra compact transverse shock wave ferromagnetic generator as the seed source and an ultra compact loop magnetic flux compression generator as the pulsed power amplifier.

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