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# EXPLOSIVE-DRIVEN MINI-SYSTEM BASED ON SHOCK WAVE FERROMAGNETIC SEED SOURCE AND LOOP MAGNETIC FLUX COMPRESSION GENERATOR

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## Abstract

Completely explosive pulsed power mini-systems based on the transverse shock wave ferromagnetic generator (FMG) served as a seed source and loop magnetic flux compression generator (LFCG) as a pulsed power amplifier were proposed, designed, built and tested. The physical principles and design of the developed FMG-LFCG system are described in detail. Experimental data are presented for the explosive operation and electrical performance of the system.

## I. INTRODUCTION

Development of compact autonomous pulsed power systems is very important for success in many scientific and engineering projects. Research activity in the field of compact explosive pulsed power generation has significantly increased for the past few years<sup>1</sup>. One of the results 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) [2-7]. This device does not utilize magnetic flux compression, but it is based on the physical effects of longitudinal [2, 3] and transverse [4-8] shock wave demagnetization of hard ferrimagnets and hard ferromagnets.

There are 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 [9]. Using the first approach, we also developed a new autonomous high-voltage nanosecond system [10]. 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 primary power for their operation. 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 a primary power source (seed source) and a helical FCG as a pulsed power amplifier [11, 12].

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 a primary power source and a miniature loop magnetic flux compression generator (Loop FCG) as a pulsed power amplifier.

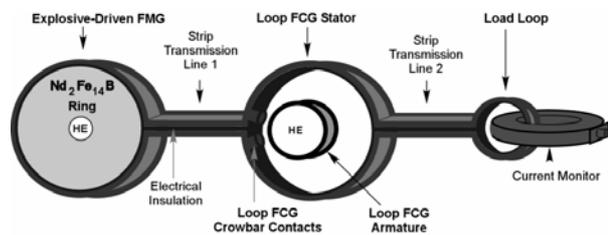


Figure 1. Schematic diagram of the completely explosive FMG-Loop FCG pulsed power mini-system developed in this work.

## II. DESIGN AND EXPERIMENTAL RESULTS

The Loop FCG was invented about 10 years ago as an explosive-driven system for operation with output current in the range of tens of mega-amperes [13]. Not much information about the Loop FCG is available in open sources. 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 Loop FCGs

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powered from conventionally charged capacitor seed sources.

A schematic diagram of the developed system that utilizes a transverse shock-wave ferromagnetic generator as a primary power source and a compact helical multi-stage FCG as a pulsed power amplifier is in Fig. 1.

The energy-carrying element of the FMG seed source (Fig. 1) was a  $\text{Nd}_2\text{Fe}_{14}\text{B}$  hard ferromagnetic ring magnetized along its axis. The high explosive charge for the generator was loaded into the central hole of the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  ring [4-8], which upon detonation initiated a transverse shock wave (the shock wave propagated perpendicular to the magnetization vector  $\mathbf{M}$ ) in the body of the ferromagnetic energy-carrying element.

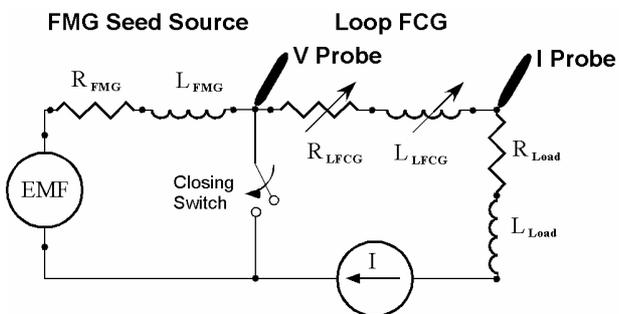
The  $\text{Nd}_2\text{Fe}_{14}\text{B}$  energy-carrying element (volume of  $25.1 \text{ cm}^3$ ) had the following dimensions: outer diameter 50.8 mm, inner diameter 7.6 mm, thickness 12.7 mm. The magnetic parameters of the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  were residual flux density 1.23 T, coercive force  $8.99 \cdot 10^5 \text{ A/m}$ , and maximum energy product  $0.279 \text{ J/cm}^3$ .

The single-turn pulse-generating coil of the FMG seed source was made of copper strip of thickness 1 mm and width 13 mm.

The FMG explosive charge included a single exploding bridge-wire RP-501 detonator bonded to one end face of the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  ring, and 0.6 g of desensitized RDX inserted in the magnet's central hole (Fig. 1).

The FMG seed source was connected to the Loop FCG by a 38 mm-long strip transmission line made of copper strip of width 13 mm. The diameter of the Loop FCG stator (loop) was 50 mm and its width was 13 mm. The Loop FCG was connected to the load loop (where the current monitor was placed) with a 38 mm strip transmission line (Fig. 1).

The equivalent circuit diagram for the two-stage explosive-driven FMG-Loop FCG pulsed power system is in Fig. 2. The equivalent circuit diagram of the FMG contains a source of electromotive force ( $EMF$ ) and a pulse-generating coil with resistance ( $R_{FMG}$ ) and inductance ( $L_{FMG}$ ). The equivalent circuit of the Loop FCG contains resistance  $R_{LFCG}$  and inductance  $L_{LFCG}$ , a closing switch (crowbar), and the load impedance  $Z_{Load}$ .

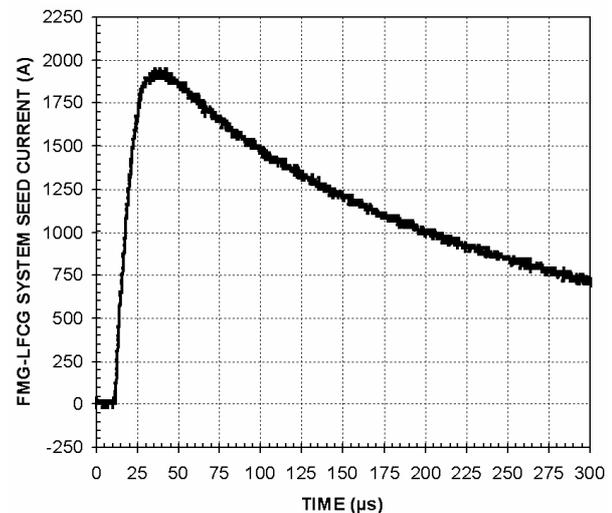


**Figure 2.** Equivalent circuit of FMG-LFCG mini-system.

The operation of the FMG seed source (Figs. 1 and 2) is based on the fundamental effect of transverse shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  hard ferromagnets [4-8]. In accordance with Faraday's law, the decrease of initial magnetic flux in the FMG due to the transverse-shock-wave compression of the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  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 Loop FCG and causes current flow in the FMG – Loop FCG – load circuit. For a single-turn coil, the generated EMF is

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

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



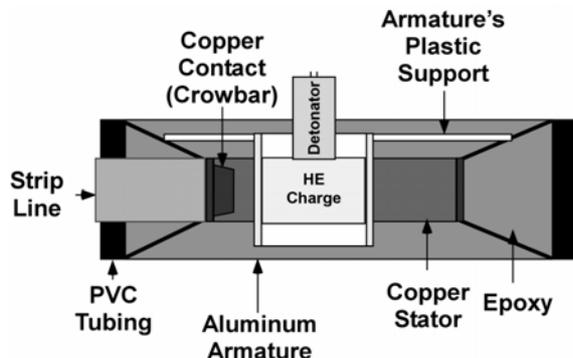
**Figure 3.** A typical waveform of the seed current produced by explosive-driven FMG across the Loop FCG-Load circuit.

We performed a series of experiments to study seed currents in the FMG – Loop FCG – load systems. It is very important to have detailed information about seed current amplitude and rise-time, in order to synchronize the electrical and explosive operation of the explosive-driven seed source and the Loop FCG. In these experiments, the high explosive charge was not loaded in the Loop FCGs. It was loaded in the FMG seed sources only.

We performed seven experiments to calibrate seed currents. In these experiments, FMGs demonstrated extremely reliable operation and very reproducible seed current amplitude and rise-times. A typical waveform of the current pulse produced by the FMG seed source is in Fig. 3. The amplitude of the current was 1931 A, with a rise time of 27.6  $\mu\text{s}$ .

After seed current calibration, we performed several series of experiments with Loop FCGs of different designs. A cut-away side view of the Loop FCG used in one of the first series of experiments is in Fig. 4. The stator of the Loop FCG was placed inside of the PVC

pipe. We encapsulated the external part of the stator along its perimeter with a high-strength epoxy inside the PVC pipe in order to keep the stator in place during explosive operation of the device.



**Figure 4.** Cut-away view of the Loop FCG developed for the first series of experiments (see the text).

The two copper cylindrical contacts of the crowbar were bolted and soldered to the stator of the FCG from both sides of the input strip line (Figs. 1 and 4). The diameter and height of each contact was 10 mm and 6 mm, respectively. Each had a slightly conical shape, and the distance between contacts was about 2 mm.

In all experiments described in this paper, we used cylindrical aluminum armatures of 25 mm diameter. The length of the armature in the first series of FMG-Loop FCG experiments was also 25 mm. In these experiments, the length of the explosive charge loaded in the central part of the armature was equal to the width of the armature of the FCG (13 mm). The charge weight varied from 6.4 to 6.7 g of desensitized RDX. A single EBW RP-80 detonator was bonded to one end of the armature (Fig. 4).

The armature was placed off-center within the stator, with the displacement towards the copper contacts of the crowbar (Figs. 1 and 4). 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 Loop FCG. The plate had a number of holes through it to weaken it in order to avoid restrictions on the armature expansion.

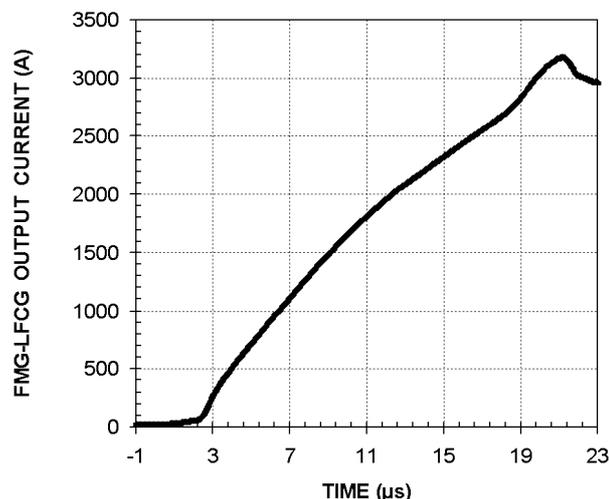
The completely explosive FMG-Loop FCG system operated as follows. The transverse shock wave in the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  energy-carrying element of the FMG produced a seed current pulse in the FMG-LFCG system. When the seed current was close to maximum, we sent the initiation pulse for the detonator of the Loop FCG. After initiation of the explosive charge in the armature of the Loop FCG, the armature expanded toward the Loop FCG stator. During the expansion, the armature closed two copper contacts in the LFCG stator (Figs. 1 and 4). 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 preliminary estimate of the amplification factor of the Loop FCG shown in Fig. 4 gave us a number from 1.6 to 2.1.

A typical waveform of the current pulse produced by the FMG-Loop FCG system in this experimental series is in Fig. 5. The amplitude of the current pulse reached 2750 A at 23  $\mu\text{s}$ . Therefore, the current gain was 1.38. The amplification factor averaged from five experiments of this series was from  $1.35 \pm 0.03$ , significantly lower than our estimation. One problem was that the current did not rise exponentially as it should have. It was evident that the Loop FCG did not operate correctly.

One possible cause of this problem is mis-alignment of the armature during its expansion. The armature should expand uniformly. We performed several series of experiments with armatures of different designs. The most successful design of the Loop FCG is in Fig. 6.

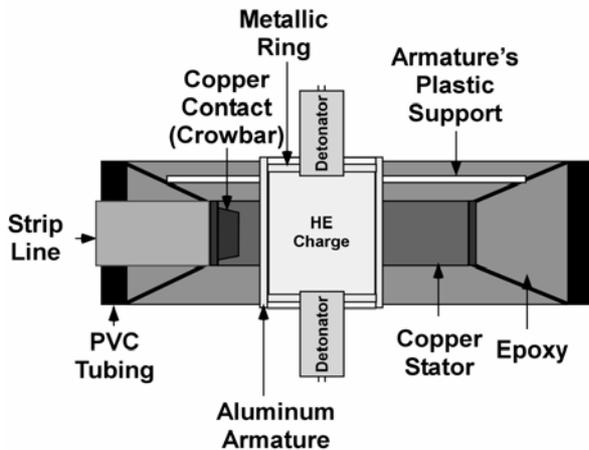


**Figure 5.** Typical waveform of the current produced by the completely explosive FMG-LFCG-Load loop system in the first experimental series with the Loop FCG design shown in Fig. 4.

The design of the new Loop FCG stator and its dimensions (Fig. 6) are similar to what we used before (see Fig. 4). The main change was in the design of the armature. The diameter of the armature was the same as before, 25 mm. The length of armature was slightly longer, 38 mm (25 mm before). The total length of the explosive charge loaded in the central part of the armature was 25 mm in this design (13 mm before). The amount of desensitized RDX loaded in the armature varied from 11 to 12 g.

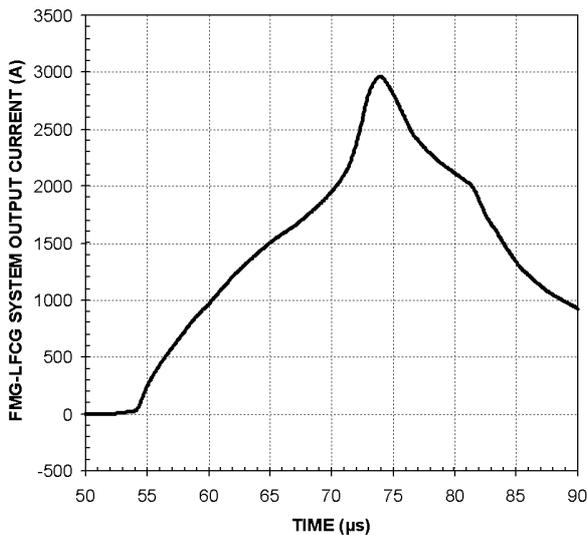
In this series of experiments, we used two RISI RP-80 EBW detonators, one bonded to each end of the armature (Fig. 6), and aligned by plastic and metallic detonator holders.

compact loop magnetic flux compression generator as the pulsed power amplifier.



**Figure 6.** Cut-away view of the Loop FCG with new armature design.

A typical waveform of the current pulse produced by the FMG-Loop FCG system (Fig. 6) is in Fig. 7. The amplitude of the current pulse reached 3170 A at 21  $\mu$ s. Therefore, the current gain was 1.7. The current rose exponentially during operation of the FCG.



**Figure 7.** Typical waveform of the current produced by the completely explosive FMG-LFCG-Load loop system in the first experimental series with the improved design shown in Fig. 6.

### III. SUMMARY

We proposed, designed, tested, 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

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