Compact Autonomous Completely Explosive Pulsed Power System Based on Transverse Shock Wave Demagnetization of $Nd_2Fe_{14}B$ and Magnetic Flux Compression

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/1179

Recommended Citation

S. I. Shkuratov et al., "Compact Autonomous Completely Explosive Pulsed Power System Based on Transverse Shock Wave Demagnetization of $Nd_2Fe_{14}B$ and Magnetic Flux Compression," *International Conference on Megagauss Magnetic Field Generation and Related Topics*, Institute of Electrical and Electronics Engineers (IEEE), Nov 2005.
The definitive version is available at https://doi.org/10.1109/MEGAGUSS.2006.4530698

COMPACT AUTONOMOUS COMPLETELY EXPLOSIVE PULSED POWER SYSTEM BASED ON TRANSVERSE SHOCK WAVE DEMAGNETIZATION OF $Nd_2Fe_{14}B$ AND MAGNETIC FLUX COMPRESSION

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

The design and performance of a compact autonomous completely explosive pulsed power system based on two physical effects, the transverse shock wave demagnetization of $Nd_2Fe_{14}B$ high-energy hard ferromagnets and magnetic flux compression, are presented. A transverse shock wave ferromagnetic generator (FMG) served as a seed source, and a compact helical magnetic flux compression generator (FCG) was used as a pulsed power amplifier. Results of a theoretical and experimental study demonstrated reliable operation of the proposed FMG-FCG system. The methodology for analytical calculation of seed current amplitude is developed.

INTRODUCTION

Scientific and engineering activity in the field of compact explosive pulsed power generation has increased for the past few years. 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) [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 [3-6] shock wave demagnetization of hard ferrimagnets and hard ferromagnets. The FMGs are capable of generating both high voltages [1-3, 7, 8] and high currents [1-6, 9]. In this work, we experimentally and theoretically studied the generation of pulsed power with compact autonomous completely explosive FMG-FCG systems.

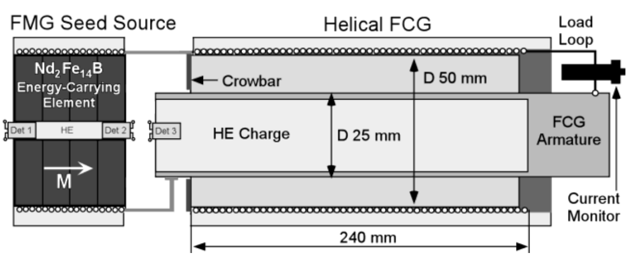


Figure 1. Schematic diagram of the FMG-FCG system.

ANALITICAL EQUATIONS FOR FMG SEED CURRENT AMPLITUDE

A schematic diagram of an autonomous completely explosive FMG-FCG pulsed power system is in Fig. 1. It contains an FMG seed source, a helical FCG, and a load.

978-1-4244-2062-9/08/$25.00 ©2008 IEEE

Operation of the FMG seed source is as follows. After detonation of the FMG explosive charge, the $Nd_2Fe_{14}B$ hard ferromagnetic energy-carrying element is subjected to shock-wave compression. The shock compression demagnetizes the element, which generates a pulsed electromotive force at the output terminals of the FMG pulse-generating coil [1-6]. Thus, the initial magnetostatic energy of a $Nd_2Fe_{14}B$ hard ferromagnet is transformed into pulsed power. The electromotive force pulse produced by the FMG is applied to the FCG-Load circuit and it produces current in the FMG-FCG-Load system.

The initial electromagnetic energy of the FMG-FCG system (Fig. 1), $W_{\text{FMG-FCG}}$, is equal to the magnetostatic energy of $Nd_2Fe_{14}B$ hard ferromagnetic element, W_{NdFeB}:

$$W_{\text{FMG-FCG}} = W_{\text{NdFeB}} \qquad (1)$$

The W_{NdFeB} is transformed into the energy of a seed current pulse. In the assumption that ohmic losses in the FMG-FCG system are negligible, the energy of the system during the seeding process, W_{seed}, is:

$$W_{\text{seed}} = [L_{\text{total}} \cdot (I_{\text{seed max}}(t))^2]/2 \qquad (2)$$

where $I_{\text{seed max}}(t)$ is the amplitude of the seed current pulse, the total inductance of the system, L_{total}, is a sum of inductances of an FMG, an FCG, and a load:

$$L_{\text{total}} = L_{\text{FMG}} + L_{\text{FCG}} + L_{\text{Load}}. \qquad (3)$$

Taking into account that FMG has an efficiency coefficient, η_{FMG}, the final equation for initial energy of the FMG-FCG system can be expressed as follows:

$$W_{\text{seed}} = \eta_{FMG} \cdot W_{\text{NdFeB}} = [(L_{\text{FMG}} + L_{\text{FCG}} + L_{\text{Load}}) \cdot (I_{\text{seed max}}(t))^2]/2 \qquad (4)$$

Eq. (4) gives the value of the seed current amplitude:

$$I_{\text{seed max}}(t) = \eta_{\text{current FMG}} \cdot [(2 \cdot W_{\text{NdFeB}})/(L_{\text{FMG}} + L_{\text{FCG}} + L_{\text{Load}})]^{1/2} \qquad (5)$$

where, $\eta_{\text{current FMG}} = (\eta_{\text{FMG}})^{1/2}$ is the coefficient of FMG efficiency for the conversion of initial magnetostatic energy, W_{NdFeB}, into a current pulse.

Note that we obtained Eq. (5) as a direct result of the application of the energy conservation law to the FMG-FCG autonomous system. Moreover, we do not make any assumptions about the physical mechanism of shock-wave demagnetization of the ferromagnet. Thus Eq. (5) can be used for operational analysis of both longitudinal [1,2] and transverse [3-6] shock-wave FMGs.

The initial magnetostatic energy, W_{NdFeB}, can be estimated as the product of the volume of the ferromagnetic element, Vol, and its maximum energy product, BH_{max}:

$$W_{\text{NdFeB}} = Vol \cdot (BH_{\text{max}}) \qquad (6)$$

Hence, from Eqs. (5) and (6) we can find the expression for $\eta_{\text{current FMG}}$:

$$\eta_{\text{current FMG}} = I_{\text{seed max}}(t)/[(2 \cdot Vol \cdot (BH_{\text{max}}))/(L_{\text{FMG}} + L_{\text{FCG}} + L_{\text{Load}})]^{1/2} \qquad (7)$$

Consider the autonomous completely explosive miniature FMG-FCG system we developed earlier [9] and determine $\eta_{\text{current FMG}}$ for this system. Electrical parameters of the FMG-FCG system [9] were as follows: L_{FMG} = 1.97 μH, L_{FCG} = 5.05 μH, L_{Load} = 0.325 μH. The amplitude of the seed current produced in the system was $I_{\text{seed max}}(t)$ = 226 ± 4 A. The volume of the ferromagnetic energy-carrying element of the FMG seed source [9] was 8.76 cm^3. The energy product of the $Nd_2Fe_{14}B$ (Grade 35) used in all experiments [1-9] was 0.279 J/cm^3.

Substituting the parameters of the system [9] into Eq. (7) we obtain $\eta_{\text{current FMG}}$ = 0.277. Thus, we conclude that in this experimental system the transverse shock-wave FMG converted the initial magnetostatic energy of the $Nd_2Fe_{14}B$ hard ferromagnetic element into current pulse with an efficiency of 27.7%.

Table 1 shows the results of additional experimental analysis we performed with high-current FMG-Load systems [4-5]. It follows from Table I that $\eta_{current\ FMG}$ coefficient is essentially constant for our system. It ranges from 0.271 to 0.283.

Table 1. Experimental results and $\eta_{current\ FMG}$ coefficient for FMG-Load systems [4-5].

FMG pulse-generating coil	Volume of $Nd_2Fe_{14}B$, Vol (cm^3)	Energy of $Nd_2Fe_{14}B$, W_{NdFeB} (J)	Total inductance of the system, L_{total} (μH)	Current amplitude, $I_{max}(t)$ (A)	$\eta_{current\ FMG}$
8.5-turns	8.76	2.44	1.14	574	0.277
Single coaxial turn	8.76	2.44	0.097	1920	0.271
Single coaxial turn	25.1	7.0	0.108	3030	0.278
Single coaxial turn	25.1	7.0	0.064	4190	0.283

The average $\eta_{current\ FMG}$ coefficient found from analysis of results obtained with FMG-FCG-Load systems [9] and FMG-Load systems [4-5] (Table I) is $\boldsymbol{\eta_{current\ FMG} = 0.277 \pm 0.007}$.

Consider the seeding process based on the magnetic flux conservation law. Before the operation of the completely explosive system the initial magnetic flux of the FMG-FCG-Load system, $\Phi_{initial\ FMG\text{-}FCG\text{-}Load}$, is the magnetic flux that is coupled by the FMG pulse-generating coil wound on the $Nd_2Fe_{14}B$ hard ferromagnet:

$$\Phi_{initial\ FMG\text{-}FCG\text{-}Load} = \sum_{n=1}^{N} \Phi_n \tag{8}$$

where Φ_n is the magnetic flux coupled with the n-th turn, and N is the number of turns in the FMG coil. This is the magnetostatic energy stored in the pulsed power system before its explosive operation. The value of Φ_n depends on the magnetic parameters and shape of the ferromagnet, and on the disposition of the n-th turn on the ferromagnet [5-6]. Thus, Φ_n can be calculated; in addition, we developed and described the methodology for calculation of magnetic flux coupled by the FMG pulse-generating coils in [5].

During explosive operation of the FMG seed source the $Nd_2Fe_{14}B$ element is subjected to shock wave compression and shock demagnetization [1-6]. The magnetic flux stored in the ferromagnet is transformed into the magnetic flux produced by the seed current, $\Phi_{seed\ current}$(t), flowing through FMG-FCG-Load circuit:

$$\Phi_{initial\ FMG\text{-}FCG\text{-}Load} = \sum_{n=1}^{N} \Phi_n = \Phi_{seed\ current}(t)_{max} = (L_{FMG} + L_{FCG} + L_{Load})\cdot I_{seed}(t)_{max} \tag{9}$$

It follows from the flux conservation law that the initial magnetic flux, $\Phi_{initial\ FMG\text{-}FCG\text{-}Load}$ (Eq. 9), must be conserved in the FMG-FCG-Load system (with the assumption that losses are negligible). Thus, for the seed current amplitude, $I_{seed}(t)_{max}$, in the FMG-FCG-Load system we obtained a system of two independent equations. The first equation is Eq. (5). The second equation can be obtained from Eq. (9):

$$I_{seed}(t)_{max} = \{\sum_{n=1}^{N} \Phi_n\}/(L_{FMG} + L_{FCG} + L_{Load}) \qquad (10)$$

This system [Eqs. (5) and (10)] may be solved by the method of successive iterative calculations. The general method is as follows:

(1) Make an assumption that $L_{FMG} = 0$. In this case, Eq. (5) gives the first approximation of the seed current value, $I_{seed}(t)^{1st\ approx}$.

(2) The substitution of the $I_{seed}(t)^{1st\ approx}$ in Eq. (10) gives the first approximation for initial value of magnetic flux of the system, $(\sum_{n=1}^{N} \Phi_n)^{1st\ approx}$.

(3) $\Phi_n\{\Phi_1, \Phi_2 \ldots \Phi_n\}$ matrix is used to find the number, N, and the dispositions for N turns of the FMG coil that should be wound on the ferromagnet for a given value of $(\sum_{n=1}^{N} \Phi_n)^{1st\ approx}$. A detailed description of the technique for calculation of the magnetic flux coupled by an FMG coil can be found in [5]. Thus, the design of the FMG seed source (number of turns, N, and dispositions of the turns) is calculated in the first approximation.

(4) This design has an exact value for FMG inductance, $L_{FMG}{}^{1\text{-}st\ iteration}$. Make the assumption that $L_{FMG} = L_{FMG}{}^{1\text{-}st\ iteration}$. In this case, Eq. (5) gives the second approximation value for seed current, $I_{seed}(t)^{2nd\ iteration}$. It is obvious that $I_{seed}(t)^{2nd\ iteration} < I_{seed}(t)^{1st\ iteration}$.

(6) The substitution of $I_{seed}(t)^{2nd\ approx}$ in Eq. (10) gives the second approximation for the initial magnetic flux of FMG-FCG-Load system. And so on. In practice, four iterations are enough to get $I_{seed}(t)^{5th\ iteration} \approx I_{seed}(t)^{4th\ iteration}$.

EXPERIMENTAL RESULTS AND DISCUSSION

A schematic diagram of the FMG-FCG system developed in this work is in Fig. 1. It contained a transverse-shock-wave FMG seed source, a helical FCG with variable inductance, and a load loop. The FMG seed source consisted of an $Nd_2Fe_{14}B$ hard ferromagnetic energy-carrying element, a high explosive charge, two detonators, and a pulse-generating coil.

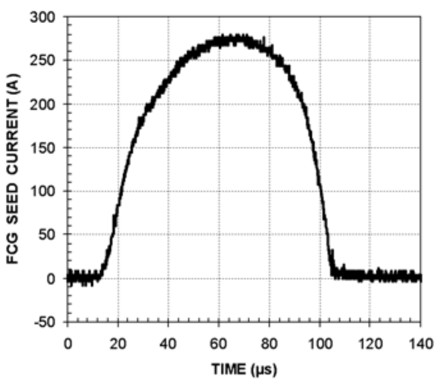
The $Nd_2Fe_{14}B$ energy-carrying element of the FMG was comprised of four identical $Nd_2Fe_{14}B$ (Grade 35) hollow ferromagnetic cylinders magnetized along their axes. The dimensions of each cylinder were as follows: outer diameter (O.D.) = 50 mm, inner diameter (I.D.) = 8 mm and length (h) = 25 mm. The overall dimensions of the $Nd_2Fe_{14}B$ energy-carrying element of the FMG were O.D. = 50 mm/h = 100 mm and its volume was 194.8 cm^3. The magnetic parameters of the $Nd_2Fe_{14}B$ used in these experiments are residual flux density, 1.23 T, coercive force, 8.99 10^5 A/m, and maximum energy product, 0.279 J/cm^3.

The FMG pulse-generating coil contained a 35-turn of heavily insulated AWG-14 copper wire. The typical inductance (at 100 kHz) of the FMG used in these experiments was 33.6 μH, and the equivalent serial resistance (100 kHz) was 0.44 Ω. The mass of the desensitized RDX explosive charge loaded in the central hole of the $Nd_2Fe_{14}B$ ferromagnetic assembly varied from 11 to 13 g. We used RISI RP-501 exploding bridge-wire (EBW) detonators.

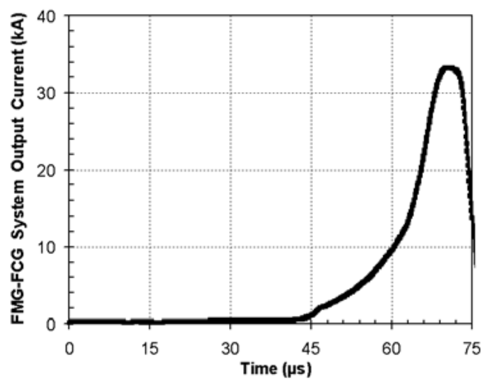
The helical FCG developed in this work (Fig. 1) contained an aluminum armature of O.D. = 25 mm, a crowbar, a stator of I.D. = 50 mm (the same as a diameter of the $Nd_2Fe_{14}B$ energy-carrying elements in the FMGs), and a load loop. The FCG stator was a multi-turn coil of variable inductance. The length of the stator was 240 mm. The electrical parameters of the helix in a typical FCG and a load loop used in these experiments were serial inductance (100 kHz) = 63.3 μH and serial resistance (100 kHz) = 1.16 Ohm.

We connected one output terminal of the FMG coil directly to the input terminal of the helix of the FCG, and the other terminal of the FMG coil to the front end of the aluminum armature of the FCG. We then connected the output terminal of the helix of the FCG to the input of the load loop, and the output of the load to the back end of the armature of the FCG.

Before performing experiments with FMG-FCG-Load systems, we calculated the seed current produced by the FMG seed source using the technique described in previous section of this paper. All parameters of the FMG-FCG system are presented above. Upon substituting the parameters of the FMG-FCG-Load system, and the $\eta_{current\ FMG}$ coefficient determined from our previous experiments, into Eq. (5) we obtained a seed current amplitude of 293 A.



(a)



(b)

Figure 2. The waveform of the seed current pulse produced in the helix of the FCG by the FMG seed source (calibration experiments) (a) and current produced by the completely explosive FMG-FCG-Load system (b).

We performed a series of experiments for calibration of the seed current in the FMG-FCG-Load system. In these experiments, the armature of the FCG was not loaded with high explosives (HE); HE was loaded in the FMG seed source only. A typical waveform of the seed current pulse produced by the FMG seed source in the helix of the FCG is in Fig. 2(a). The current risetime (τ) was 49.5 μs, and the amplitude of the current pulse was $\boldsymbol{I_{seed\ max\ exp}(t) = 280}$ **A**. The amplitude of the seed current averaged from four experiments was $I_{seed\ max\ exp}(t)$ **= 287 ± 4 A**, so one can conclude that the calculated and experimental seed current amplitudes are in very good agreement.

By substituting the total inductance of the FMG-FCG-Load system, 96.9 μH, and the experimentally obtained seed current amplitude into Eq. (9), we can determine the magnetic flux produced by the seed current, 27.8 mWb. Using Eq. (8) we calculated that the magnetic flux coupled by a FMG coil before explosive operation was 33.7 mWb. Based on the comparison of these two values, we conclude that using slightly less than 35 turns in the pulse-generating coil of the FMG seed source could improve its performance.

A typical waveform of the current produced by the completely explosive FMG-FCG-Load system is in Fig. 2(b). The FCG armature was loaded with 197 g of HE. We detonated the explosive charge in the FCG armature 39 μs after detonation of the FMG explosive charge, to allow for crowbar within the FCG at the peak seed current amplitude. The FCG output current amplitude was 33.13 kA, and τ was 27 μs. In this experiment, we achieved a current amplification factor of $G_I = 114$.

REFERENCES

1. Shkuratov, S.I., Talantsev, E.F., Dickens, J.C., Kristiansen, M. and Baird, J. "Longitudinal-shock-wave compression of $Nd_2Fe_{14}B$ hard ferromagnet: the pressure induced magnetic phase transition," *Appl. Phys. Letters*, Vol. 82, 2003, pp. 1248-1251.
2. Shkuratov, S.I., Talantsev, E.F., Dickens, J.C., Kristiansen, M. "Compact explosive-driven generator of primary power based on a longitudinal shock wave demagnetization of hard ferri- and ferromagnets," *IEEE Transaction on Plasma Science*, Vol. 30, 2002, pp. 1681-1691.
3. Shkuratov, S.I., Talantsev, E.F., Dickens, J.C., Kristiansen, M. "Transverse shock wave demagnetization of $Nd_2Fe_{14}B$ high-energy hard ferromagnetics," *J. Appl. Phys.*, Vol. 92, 2002, pp. 159-162.
4. Shkuratov, S.I., Talantsev, E.F., Dickens, J.C., Kristiansen, M. "Ultracompact explosive-driven high-current primary source based on shock wave demagnetization of $Nd_2Fe_{14}B$ hard ferromagnetics," *Rev. Sci. Instrum.*, Vol. 73, 2002, pp. 2738-2742.
5. Shkuratov, S.I. and Talantsev, E.F. "Powering the coaxial single-turn seed coil of a magnetocumulative generator by an explosive-driven shock wave ferromagnetic primary source", *Journal of Electromagnetic Phenomena*, Vol. 3, No. 4(12), 2003, pp. 452-467.
6. Shkuratov, S.I., Talantsev, E.F., Dickens, J.C., and Kristiansen, M. "Currents produced by explosive driven transverse shock wave ferromagnetic source of primary power in a coaxial single-turn seeding coil of a magnetocumulative generator", *J. Appl. Phys.*, Vol. 93, 2003, pp. 4529-4535.
7. Shkuratov, S.I., Talantsev, E.F., Baird, J., Altgilbers, L.L., and Stults, A.H. "Compact autonomous explosive-driven pulsed power system based on a capacitive energy storage charged by a high-voltage shock-wave ferromagnetic generator", *Rev. Sci. Instrum.*, Vol. 77, 2006, pp. 066107-1-5.
8. Shkuratov, S.I., Talantsev, E.F., Baird, J., Altgilbers, L.L., and Stults, A.H. "Completely explosive autonomous high-voltage pulsed power system based on shock wave ferromagnetic primary power source and spiral vector inversion generator", *IEEE Transaction on Plasma Science*, Vol. 34, No. 5, 2006, pp. 1866-1872.
9. Talantsev, E.F., Shkuratov, S.I., Dickens, J.C., and Kristiansen, M. "Completely explosive pulsed power minisystem," *Rev. Sci. Instrum.*, Vol. 74, 2003, pp. 225-230.