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Electric discharge caused by expanding armatures in flux compression generators

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In this letter, we experimentally demonstrate that explosively driven expansion of metallic armature of the magnetic flux compression generator (FCG) plays a dominant role in the formation of plasma and electric discharge initiation inside the FCG. © *2009 American Institute of Physics.*
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There are several types of electric discharge phenomena that cause energy losses in pulsed power systems.[1] Initiation of electric discharges in helical magnetic flux compression generators (FCGs) was reported earlier.[2,3] It was shown in Ref. 2 that the electric discharge is not itself a source of magnetic flux loss in the FCG; however, high current densities created by the discharge in the armature and the stator of the FCG increase the rate of flux diffusion into the conductors that causes flux loss in the generator. It was demonstrated that flux loss in the FCGs increases about 50% due to the electric discharge.[2]

In order to obtain detailed information about the initiation and development of electric discharges during different stages of the operation of FCGs, we performed experimental studies based on the simultaneous recording of electric signals produced by FCGs and high-speed photography of its operation. Experiments were conducted with loop magnetic flux compression generator (LFCG).[4] The explosive and electrical operation of a loop FCG are similar to that of other types of FCGs (i.e., coaxial FCGs and helical FCGs) based on magnetic flux compression inside the stator due to the explosively driven expansion of a cylindrical armature.[5] The specific feature of an LFCG that made it useful for these experiments is the opportunity to observe in detail the processes that occur inside the generator (expansion of the armature, closing the crowbar contacts, etc.) from the very beginning until the final stage of its operation, something that cannot be done when studying helical, coaxial, or other types of flux compression generators. Results obtained with the miniature LFCG developed for these studies (Fig. 1) can be used to better understand the initiation of the electrical discharge in LFCGs of larger sizes and in helical and coaxial FCGs.

We performed high-speed photography of the LFCG operation with a Cordin 10 A framing camera (Fig. 1). To avoid any shock-induced glow in the atmosphere around the LFCG during its operation, we put the generator in a disposable wooden box that we purged with helium immediately before initiating the experiment.

To avoid the effect of external electric circuits and external electric potentials on the initiation and development of the electric discharge in the LFCG, we utilized an autonomous explosively driven shock-wave ferromagnetic generator (FMG)[6,7] as a seed source for the LFCG. The FMG generated an initial current, I_{seed}, thereby creating an initial magnetic flux in the FCG-load circuit. The FMG-LFCG-load pulsed power systems that we studied were completely autonomous, being powered exclusively by high explosives with no external electrical circuits or power supplies.

The stator of the LFCG was made of a bare copper strip 12.7 mm wide and 1.0 mm thick, with a 50.0 mm inner diameter (ID) (Fig. 1). The cylindrical armature of the LFCG was made of 6601 aluminum alloy tubing of 25.4 mm outer diameter, 22.4 mm ID, and 37.5 mm length. The length of the high explosive (HE) charge loaded inside the armature of the LFCG was 19.0 mm (10.2 g of C-4) with two RP-80 detonators, one attached at each end of the charge.

Figure 2 presents a series of high-speed photographs (500 000 frames/s) of the explosive operations of the FMG-LFCG system. Figure 3 shows the corresponding waveform of the current pulse produced by the FMG-LFCG system along with the seed current waveform and the FMG output voltage waveform. The waveforms in Fig. 3 are marked with letters that correspond to the letters marking the photos in Fig. 2. In the photographs shown in Fig. 2, the FMG is on the left and the LFCG is on the right. All parts of the FMG-LFCG system are captioned in Fig. 2(a).

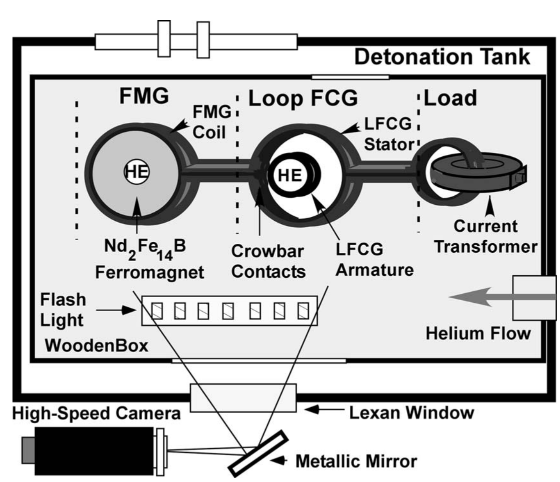

FIG. 1. A schematic diagram of the experimental setup for high-speed photography of explosive and electrical operation of FMG-LFCG-load system.

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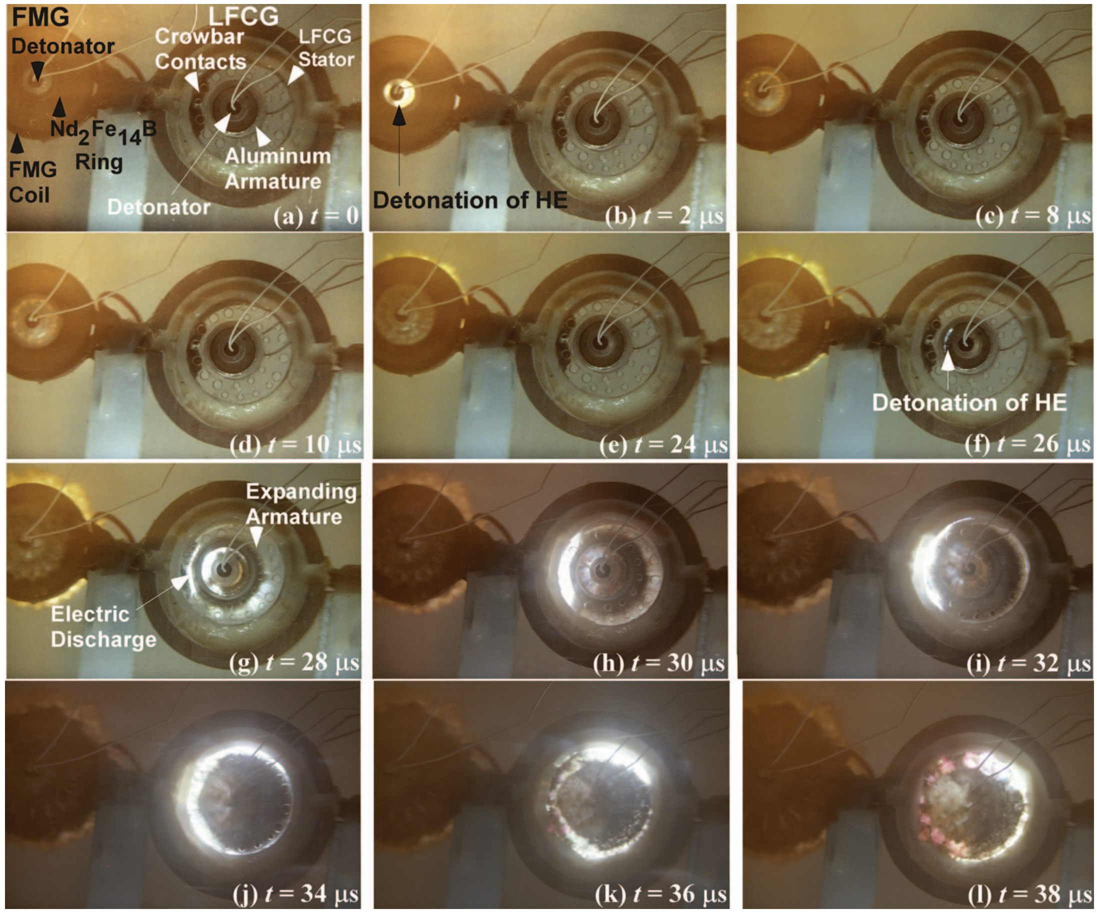

FIG. 2. (Color) A series of high-speed photographs taken during explosive and electrical operation of FMG-LFCG-load system.

At $t=0$ μs, the detonators of the FMG seed source were initiated [Fig. 2(a)], detonating the HE charge loaded in the central hole of the $Nd_2Fe_{14}B$ hard ferromagnetic ring. There is a bright light clearly visible in the central hole of $Nd_2Fe_{14}B$ ferromagnet [Fig. 2(b)] due to the initiation of the HE charge. The HE charge was in direct contact with the $Nd_2Fe_{14}B$; as such, the transverse shock wave from the explosive detonation propagated through the body of the $Nd_2Fe_{14}B$ ring from its central hole to its periphery. Due to the transverse shock demagnetization of the $Nd_2Fe_{14}B$, the FMG seed source produced a pulsed voltage at the input of the LFCG (across the contacts of the crowbar). The voltage reached its peak amplitude at $t=10$ μs [Figs. 2(d) and 3], and $U_{crowbar}(10\ \mu s)=35.4$ V. The seed current reached its maximum at $t=28$ μs [Figs. 2(g) and 3], $I_{seed}(28\ \mu s)_{max}=2.6$ kA. The inductances of the LFCG and the load (measured with a Quadtech 7600 *LCR* meter) in this experiment were $L_{LFCG}(100\ kHz)=72$ nH and $L_{load}(100\ kHz)=57$ nH, respectively. At $t=28$ μs, the magnetic flux produced by the FMG in the LFCG-load system reached its maximum $\Phi_0(28\ \mu s)_{max}=335$ μWb.

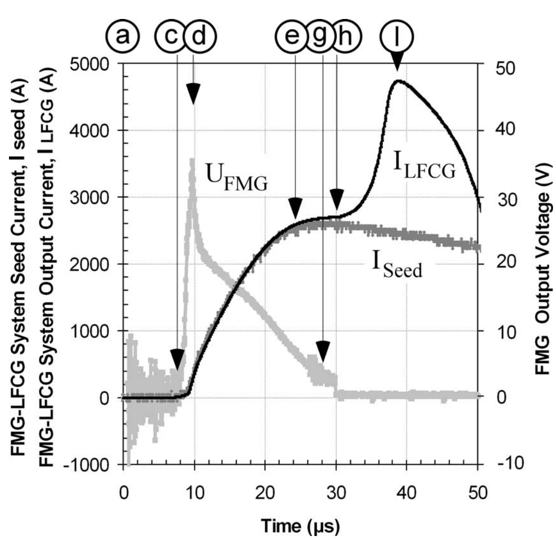

FIG. 3. Waveforms of the output voltage pulse (light gray) and seed current pulse (dark gray) produced by the FMG seed source in the LFCG-load system, and the waveform of the current pulse produced by the completely explosive FMG-LFCG-load system (black).

The detonators of the LFCG were initiated with a delay of $t_d=24$ μs after the initiation of those in the FMG. In Fig. 2(f), one can see the light due to the detonation of the HE inside the armature of the LFCG. The denotation wave moved through the HE charge inside the aluminum armature for a period of 1.2 μs. It took 0.2 μs for the shock-wave front to pass through the walls of the armature, after which it entered the gas (helium in this case) in the surrounding space. The shock-wave front propagated through the gap between the armature and the crowbars of the LFCG for 3.2 μs and then reached the stator. Due to the action of the high pressure gases from the detonation of the HE charge inside the aluminum armature of the LFCG, the armature started its expansion (the expanding armature is the dark contour in the photographs [Figs. 2(g)–2(i)]).

At the moment when the armature started its expansion, plasma appeared in the gap between the armature and the crowbar and in the gap between the contacts of the crowbar [Fig. 2(g) ($t=28$ μs)]. The voltage between the crowbar contacts (two copper cylinders of 10 mm diameter, 5 mm length, and 1.5 mm edge radius, with a 2.5 mm gap between them) was very low, $U_{\text{crowbar}}(28\ \mu\text{s})=3.6$ V (Fig. 3), and the corresponding electric field strength is estimated to be $E_{\text{crowbar}}(28\ \mu\text{s})=0.07$ kV/cm. The electric field was definitely not high enough to initiate an electric discharge in helium.[1] Therefore, the initiation and development of the electric discharge in the LFCG as seen in Fig. 2 cannot be directly related to high electric fields in the system.

Direct evidence of the critical role of the explosively expanding armature in the formation of plasma and in the initiation of an electric discharge in the FCG is the fact that the discharge at the crowbar was not initiated at the time of highest voltage across the contacts, $t=10$ μs [Figs. 2(d) and 3], which was prior to the start of armature expansion. At $t=10$ μs, the voltage across the crowbar contacts was $U_{\text{crowbar}}(10\ \mu\text{s})=35.4$ V (Fig. 3) and the corresponding electric field strength was estimated to be $E_{\text{crowbar}}(10\ \mu\text{s})=0.7$ kV/cm. Therefore, the voltage across the contacts of the crowbar at $t=10$ μs was almost an order of magnitude higher than that at the time the armature expansion began, $t=28$ μs.

At $t=30$ μs [Figs. 2(h) and 3], the expanding armature made contact with the crowbar and closed it. At that moment, the FMG seed source was disconnected from the FCG-load circuit and magnetic flux was trapped in the LFCG between the stator and the expanding armature. A bright light appeared at the contact point between the armature and the crowbar [Fig. 2(h)] due to plasma arising from the intense electric discharge that occurred when the armature approached the crowbar and made contact.

After $t=30$ μs, continued expansion of the armature led to the compression of the magnetic flux in the LFCG, resulting in amplification of the current in the load (Fig. 3). The expansion of the armature was accompanied by the generation of a plasma that filled the gap between the armature and the stator [Fig. 2(i)–2(k)].

At $t=38$ μs, an intense plasma was distributed along the entire perimeter of the stator, including the output terminals of the LFCG [Fig. 2(l)]. Apparently, this plasma short-circuited the output terminals of the LFCG at that point and shut off the continued increase in the output current. The current reached a peak amplitude value at $t=38$ μs, $I_{\text{final}}(38\ \mu\text{s})=4730$ A (Fig. 3). The total magnetic flux loss in this experiment was $\Delta\Phi=66$ μWb. Magnetic flux loss averaged from four experiments of this series was $\Delta\Phi_{\text{aver}}=66\pm7$ μWb.

The formation of plasma and initiation of the electric discharge within the stator of the LFCG is probably the result of two different shock processes in the gas between the stator of the LFCG and the expanding armature. The first shock process results from the detonation of the HE inside the armature. Passage of this detonation shock through the LFCG compresses, heats, and excites the gas within the flux compressor.[8]

After the detonation shock front propagates through the gas, the armature begins its expansion (see timing above). Based on high-speed photograph images, the speed of the expansion is 1.6 ± 0.1 mm/μs at the initial stage of the expansion and 2.9 ± 0.1 mm/μs at the final stage. This is nearly three times faster than the normal acoustic velocity of the gas fill; therefore, gas in the path of this expansion forms a shock. This second shock builds in front of the expanding armature in the gas, recompressing the already shocked gas. The compression process results in greater heating, and therefore, greater excitation of the gas immediately in front of the expanding armature when compared to the excitation caused only by passage of the detonation shock.

As a result of the two shock processes happening in quick succession, a part of the gas is ionized and plasma is formed in the gas between the armature and the stator.[8] The appearance of plasma causes the initiation of the electric discharge in the system even at very low electric fields. It is obvious that plasma formation processes observed and herein described take place in helical and coaxial FCGs too, where cylindrically expanding armatures also cause formation of plasma and initiation of the electrical discharges.

In conclusion, we demonstrated the dominant role of the explosively expanding metallic armature in the formation of plasma and in the initiation of an electric discharge in the FCG. Because of the hydrodynamic performance of the conducting and insulating materials under the loading within the generator there are no design-independent thresholds for the formation of plasma and initiation of discharge; the thresholds will depend on the shape and placement of the conductors and insulators, and on the materials used for each. Repeated shocking of the materials between the expanding armature and the stator makes it difficult to provide effective electrical insulation within the FCG from the beginning until the final stage of its explosive and electrical operation. Solving this problem will require a thin film insulator that cannot be ionized by multiple shocks. Electrical insulation coating of the crowbar and stator would probably provide a delay in the development of the discharge. Although the effect of electric discharge on flux loss is unknown in this particular configuration, the cause of the electric discharge does seem to be from the shocks produced by the expanding armature.

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