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# EXPLOSIVE GENERATORS

PHYSICS

1967

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## Abstract

## Full Text

UDC 538.4

PHYSICS

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# EXPLOSIVE GENERATORS

*(Presented by Academician A. D. Sakharov, 11 IV 1966)*

The high energy density and great power developed upon detonation in chemical explosives appear very attractive for use in a number of areas of experimental physics and technology.

For converting the energy of explosives into the energy of a magnetic field, it has been proposed to use rapid compression of conductors with trapped magnetic flux—magnetic cumulation<sup>(1)</sup>. By this method it has proved possible to obtain a magnetic field of  $(1 \div 2) \cdot 10^7$  oersted and powerful current pulses of  $5 \cdot 10^7$  A<sup>(1, 2)</sup>. Certain questions associated with the compression of an axial field were considered in<sup>(3)</sup>. It has been proposed to use strong magnetic fields obtained by explosion for confining and heating dense plasma<sup>(4)</sup>.

The present article sets forth the results of work carried out at the Institute of Hydrodynamics of the Siberian Branch of the USSR Academy of Sciences on the creation of explosive devices that convert the energy of explosives into the energy of a magnetic field. Such devices were called explosive generators.

An explosive generator is a system with variable inductance, decreasing during the operation of the generator. In this process, the conductors set in motion and accelerated by the explosion do work against the ponderomotive forces of the magnetic field, which leads to an increase in the field energy.

The initial inductance of the generator  $L_0$  depends on the inductance of the load  $L_n$ , the initial energy  $E_0$ , and the energy  $E$  delivered to the load, and was chosen in accordance with the relation

$$L_0 \gg \left( \frac{E}{E_0} - 1 \right) L_n,$$

obtained under the assumption of the absence of flux losses, which is sufficiently justified if the quantity  $4\pi\sigma va/c^2 \gg 1$ <sup>(5, 6)</sup> ( $v$  is the velocity,  $\sigma$  the conductivity,  $a$  the size of the region occupied by the field) and if no disturbances occur in the operation of the generator leading to the capture of part of the flux in the cavity formed when the moving conductors close.

Fig. 1. Two-bus profiled generator

Figure 1: Fig. 1. Two-bus profiled generator

The maximum magnetic field in the generator was chosen as a function of its mechanical strength. In doing so, account was taken of the danger of overheating of the skin layer, accompanied by ejection of metal and loss of conductivity (<sup>7</sup>, <sup>8</sup>), as well as of the charge design and the type of explosive used. The minimum field is determined by the effectiveness of braking the conductor over the permissible displacement of it without destruction by the explosion and without the appearance of possible instabilities of motion. Therefore, in the generators tested, measures were taken so that the initial field was of the order of  $10^5$  oersted, while the maximum field was limited to  $10^6$  oersted.

The operating time of the generator is bounded above by the relaxation time of the magnetic flux, and below by the magnitude of the permissible stresses, the energy, and the inductance of the load.

The magnetic flux in the generator was produced by the discharge of a capacitor bank. In each experiment, the discharge current of the bank and the current in the load during operation of the generator were oscillographed; the latter was always measured

by no fewer than two belts differing in sensitivity. Usually the current and the time derivative of the current in the load were recorded. When installing the belts, measures were taken to protect the belts and the measuring cables from the action of shock waves and fragments. Two independent measurements of the current in the load, obtained in each experiment, differed by no more than 15%.

Two types of low-inductance generators were tested: a two-bus generator and a coaxial generator. One of the tested two-bus generators is shown in Fig. 1. The width of the buses and the distance between them varied along the length of the generator. Over a 3-cm section the buses diverged to a distance

### Fig. 1. Two-bus profiled generator

of 3 cm and then were arranged in parallel over a length of 10 cm, after which they were bent and brought together toward the load (a small single-turn solenoid,  $L_n \approx 6-7$  nH) to a distance of 3-5 mm between them. The bus width was 15 mm over a length of 30 cm; then, over 10 cm, the buses gradually widened to 70 mm. The buses were made from sheet copper 1.5 mm thick. The layer of explosive was 10 mm thick and decreased on the wide section of the buses to 5 mm. An insulated wide strip of copper was placed between the buses (not shown in Fig. 1). The inductance of the generator was  $\sim 180$  nH.

The generator described operated stably at initial currents  $(90 \div 95) \cdot 10^3$  A, providing an increase of the current in the load by a factor of 17-22. The final current in this case reached  $(1.6 \div 2) \cdot 10^6$  A.

Fig. 2. Coaxial generator

Figure 2: Fig. 2. Coaxial generator

Increasing the initial currents by a factor of 2-3 led to the result that, during the operating time of the generator, the buses had time to deform noticeably under the action of the strong magnetic field, and the charge located at the end of the generator produced a premature short-circuiting of the input to the load, leaving in the generator an inductance considerable in comparison with that of the load. As a result, the efficiency of the generator decreased, and the final current even decreased somewhat despite the increase in the initial current. The use of packing and tightening of the buses improved the operation of the generator. In other experiments on the two-bus generator, programming of the current-pulse shape was carried out by changing the width of the buses and the distance between them.

A coaxial-type explosive generator is shown in Fig. 2. For its manufacture, copper tubes with a wall thickness of 2.5 mm were used. The inner diameter of the large tube was 80 mm, and the outer diameter of the small one was 30 mm. Sections of tube 58 cm long were pressed into a strong steel cup 70 mm high. The part of the coaxial line located in the cup served as the load, into which was placed a cylindrical Plexiglas ring with a circular groove for laying the belts. The inductance of the generator with the load was 110 nH, and the inductance of the load was 14 nH. The explosive charge was poured into the inner tube, which was cut into 4 parts along generatrices; this was intended to eliminate the danger of its rupture in the transverse direction and, as the experiments showed, had little effect on the process of compressing the flux. The length of the explosive charge was 51 cm, and the total weight about 380 g, i.e., the energy reserve was  $(1.9 \div 2) \cdot 10^6$  J.

The experiments were carried out at initial currents  $(2 \div 8.2) \cdot 10^5$  A. In all series of experiments an increase of the current by a factor of  $7.9 \div 8.1$  was obtained.

Figure 3 shows an oscillogram of the current and of the derivative of the current in the load at an initial current of  $8.2 \cdot 10^5$  A (it was measured with another oscilloscope). The oscilloscope was triggered with a slight lead relative to the detonation. The final current in the load was  $6.5 \cdot 10^6$  A. The energy of the magnetic field in the load was  $(2.8 \div 3) \cdot 10^5$  J. Thus, in the experiment described, 12-14% of the energy of the h.e. charge was converted into magnetic-field energy.

The initial field at the surface of the inner tube in the generator described was  $1.2 \cdot 10^5$  Oe; by the end of the generator operation it was  $9.6 \cdot 10^5$  Oe. An increase

### Fig. 2. Coaxial generator

in the field in the generator was achieved by reducing the tube diameters by a factor of 3 without changing their length. Such a generator was tested at an initial current of  $6 \cdot 10^5$  A. The current increased to  $(3.7 \div 4.2) \cdot 10^6$  A, and the

Fig. 3. Oscillogram of the current and current derivative in the load during operation of the coaxial generator. 1 –current, 2 –current derivative

Figure 3: Fig. 3. Oscillogram of the current and current derivative in the load during operation of the coaxial generator. 1 –current, 2 –current derivative

Fig. 4. Oscillogram of current and current derivative in the load during operation of a multiturn generator. 1 –current, 2 –current derivative

Figure 4: Fig. 4. Oscillogram of current and current derivative in the load during operation of a multiturn generator. 1 –current, 2 –current derivative

final field was  $(1.5 \div 1.7) \cdot 10^6$  Oe. The operation of the generator in this regime proved to be unstable.

By forming the ratio  $I'/I^2$  at different instants of time, it is possible to estimate the conservation of flux during operation of the coaxial generator. In an ideal

**Fig. 3. Oscillogram of the current and derivative of the current in the load during operation of the coaxial generator. 1 –current, 2 –derivative of the current**

generator with a constant rate of flux compression and a constant load inductance, this ratio should be constant. It was found that, within the measurement error, the value  $I'/I^2$  is constant at small initial currents and decreases somewhat at a large initial current. At the same time, the time from the beginning of detonation to the current maximum also increased from 75 to 85  $\mu\text{sec}$ .

Several generators with a large initial inductance were tested; they differed from the MK-2 generators <sup>(1)</sup> in the external arrangement of the charge and the compressing screen. In operation with such generators, encountered

considerable difficulties were encountered in making a simple solenoid capable of maintaining, for 100  $\mu\text{sec}$ , a field of the order of  $10^5$  oersted. With an initial inductance of the generator with the load of  $1.8 \div 1.9 \mu\text{H}$ , a load inductance of 50 nH, and a dense solenoid winding (1 turn/cm), it proved possible to obtain an increase of a small initial current of  $10^5$  A by a factor of 16–20. The operation of the generator took place with losses of from 1/2 to 2/3 of the initial flux and depended strongly on the quality of manufacture of the solenoid, on the symmetry of the charge and detonation, and on the relation between the solenoid and the screen. The oscillogram of the current derivative in the load (Fig. 4) is always cut by breaks, the number of which approximately corresponded to the number of turns in the solenoid. The end of the oscillogram in Fig. 4 corresponds to the compression of the flux in the coaxial section.

**Fig. 4.** Oscillogram of the current and current derivative in the load during operation of a multiturn generator. 1 –current, 2 –current derivative.

Generators based on a solenoid placed in a contracting screen worked better

when the turns were arranged sparsely (1 turn per 3-4 cm); in these generators the flux losses did not exceed 1/3. However, with these generators it has not yet been possible to obtain an efficiency of conversion of the explosive energy better than 1-2%.

To match the generator to a load of large inductance, a step-up transformer was used. This possibility was also used in work (1). It is not difficult to show that if

$$\frac{L_2 L_n}{L_2 + L_n} \frac{1}{n^2} \gg L_p \quad \text{and} \quad L_n \ll L_2$$

where  $L_2$  is the inductance of the secondary winding of the transformer,  $L_n$  is the load inductance,  $n$  is the transformation coefficient, and  $L_p$  is the leakage inductance and residual inductance in the generator, then a considerable fraction of the energy from the generator can be transferred to the load. A small coaxial generator was connected through a transformer ( $n = 3$ ) to a generator of the same magnitude. Such a two-stage circuit made it possible to obtain an average efficiency of utilization of the explosive charge energy of 8-10%.

In conclusion, the author thanks Acad. M. A. Lavrent'ev for his constant attention to the work and Acad. G. I. Budker for valuable discussions.

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Received  
4 IV 1966

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