EXTRACTION OF ENERGY FROM INDUCTIVE STORES AND EXPLOSIVE-MAGNETIC GENERATORS INTO AN INDUCTIVE LOAD USING CIRCUIT BREAKING

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INTRODUCTION

In recent years the problem of obtaining high-power current pulses using inductive energy stores has been given increasing attention. The increased interest in such devices is due to the fact that the magnetic energy density in inductive stores considerably exceeds the energy density of capacitive sources. These advantages are most obvious in the case of pulsed stores supplied from explosive-magnetic generators operating on the principle of the rapid compression of magnetic flux [1-5]. The store has low inductance in explosive systems but the currents in it may reach tens and even thousands of millions of amperes.

The record values of currents and energies obtained using explosive-magnetic generators opens up enormous prospects for the use of pulsed stores in many areas of modern physics (the study of the plasma focus [6], the achievement of high magnetic pressures for the isentropic compression of materials [7], the acceleration of charged particles to high energies, etc.).

The most widely used method of extracting the energy from an inductive store into an external load is to break the current in the store circuit. To do this switches based on the electrical explosion of fine wires [4, 8, 9] or on the mechanical destruction of the conductors by means of an explosive charge [5,10] are used. The efficiency of the energy transfer into the load depends on the resistance introduced by the switch into the breaking circuit and the ratio of the inductances of the store and the load. As pointed out in [8], the parasitic inductance on the switch has an important effect on the nature of the energy transfer into the load.

The use of explosive-magnetic generators, which are simultaneously amplifiers of the initial energy, as inductive stores requires, in addition to experimental investigations, a theoretically based approach to the choice of the fundamental components of the circuit for matching the generator parameters to the load and for generating high-power current pulses in the latter.

The purpose of the present paper is to consider the process by which the energy is extracted from steady-state inductive stores and explosive-magnetic generators into an external inductive load, taking into account the parasitic inductances of the switch, and to determine the optimal relations between the inductances of the main circuit and the load in order to obtain maximum energy in it.

1. The Efficiency of Energy Transfer from an Inductive Store into an Inductive Load Taking into Account the Parasitic Inductance of the Switch

As shown in [8], when there is parasitic inductance present in the switch, part of the initial energy is absorbed by the switch itself, leading to a reduction in the overall efficiency of the system. It is also well known [5] that the maximum energy-transfer coefficient into the load, comprising 25% of the initial amount for a noninductive switch, is attained when the inductance of the store is equal to the inductance of the load. The presence of parasitic inductance in the switch, whose value depends on the constructional features of the breaking device itself, leads to a change in the optimum conditions for energy transfer into the load.

We will determine for what inductance L_1 of the store and assigned constant inductances of the load L_2 and the switch L_3 the maximum energy-transfer coefficient into the load is achieved.

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Consider the equivalent electric circuit in Fig. 1 and assume that at the instant of time $t = 0$ the switch S connects the load L_2 to the main circuit L_1, and at this instant the switch breaks the electric circuit with inductance $L_1 + L_3$. We will assume that at the instant when breaking occurs the resistance R increases suddenly from zero to infinity.

Since the initial magnetic flux is given and is equal to Φ_0, we can write

$$\Phi_0 = I_1(L_1 + L_3).$$

Hence the currents in the store and load are given by

$$I_1 = \Phi_0/(L_1 + L_3),\ I_2 = \Phi_0 L_1/(L_1 + L_3)(L_1 + L_2).$$

The initial energy and the energy transferred to the load will be given by

$$W_0 = \Phi_0^2/2(L_1 + L_3),\quad W_2 = \Phi_0^2 L_1^2 L_2/2(L_1 + L_3)^2(L_1 + L_2)^2.$$

Consequently, the energy-transfer coefficient into the load can be written in the form

$$k = \frac{W_2}{W_0} = \frac{1}{\left(1 + \frac{L_2}{L_1}\right)^2\left(\frac{L_1}{L_2} + \frac{L_3}{L_2}\right)} = \frac{1}{\left(1 + \frac{1}{\alpha}\right)^2(\alpha + \beta)}, \tag{1.1}$$

where $\alpha = L_1/L_2$ and $\beta = L_3/L_2$ are the dimensionless quantities. It is seen from (1) that as $L_1 \to 0$ and $L_1 \to \infty$, the value of k approaches zero. This means physically that there is an optimum value of the inductance L_1 when the maximum energy-transfer coefficient is achieved. Figure 2 shows a family of curves of $k(\alpha)$ for different values of β representing the effect of the parasitic inductance of thw switch on the energy in the load. When $\beta = 0$ (the switch is noninductive), the maximum energy-transfer coefficient is obtained when $L_1 = L_2$ and, as stated earlier, is 0.25. As β increases, the energy-transfer coefficient falls, and the maximum of k is shifted toward higher values of α. This has a simple physical explanation.

Switches having a comparatively high parasitic inductance hold a considerable fraction of the initial energy, stored in the storage circuit. This portion of the energy is not transferred to the load during the breaking process and is dissipated in the resistance R. In the limiting case as $L_3 \to \infty$, all the initial energy is converted into Joule heat.

To determine the optimum value of L_1, we differentiate (1.1) with respect to α and equate the expression obtained to zero. From the quadratic equation of the form $\alpha^2 - \alpha - 2\beta = 0$ we obtain

$$\alpha_* = 1/2 + \sqrt{1/4 + 2\beta}.$$

The graph of $\alpha_*(\beta)$ is shown in Fig. 3. For a known switch inductance this graph enables one to establish the optimum inductance of the store for which maximum energy is obtained in the load inductance.

2. Efficiency of Energy Transfer from an Explosive-Magnetic Generator into an Inductive Load Taking into Account the Parasitic Inductance of the Switch and the Loss of Magnetic Flux in the Circuit Compression Process

The principle of operation and the construction of explosive-magnetic generators has been described in some detail in [3-5]. The distinguishing feature of an explosive-magnetic generator is that when the circuit is compressed, the current and energy increase (if the losses of magnetic flux are comparatively small), whereas in the usual inductive stores these quantities remain constant. It was proposed in [3] that the efficiency of the operation of an explosive-magnetic generator should be characterized by the coefficient of perfection of the system F, defined as

$$F = \ln\frac{I(t)}{I_0}\Big/\ln\frac{L_0}{L(t)}, \tag{2.1}$$

where I_0 and $I(T)$ are the initial current and the current in the circuit at the instant t, and L_0 and $L(T)$ are the intial inductance and the inductance of the circuit at the instant t. It is seen from Eq. (2.1) that the greater the value of F, the more ideal and efficient the system. It is relevant to mention that a gain in energy occurs in the explosive-magnetic generator when $F > 0.5$.

To calculate the energy-transfer coefficient from the explosive-magnetic generator into an external inductive load taking into account the coefficient of perfection F and the parasitic inductance of the switch we will consider the equivalent electric circuit in Fig. 4. In this circuit the part of the generator is played by the decreasing inductance $L_1(t)$, while the load is represented by the inductance L_2. The inductance of the switch is denoted by L_3.

We will assume that at the instant when the circuit is broken the switch resistance increases suddenly from zero to infinity. Before compression of the magnetic flux starts ($t = 0$), a current I_0 flows in the generator from the initial inductance L_0. Since the initial flux is given and is equal to Φ_0, the flux Φ_1 at the instant when the break occurs t_1, when the inductance decreases from L_0 to $L_1(t_1)$, can be represented in the form

$$\Phi_1 = \left(\frac{L_0 + L_3}{L_1 + L_3}\right)^{F-1} \Phi_0,$$

while the currents in the generator and the load are given by

$$I_1 = \frac{\Phi_1}{L_1 + L_3} = I_0 \left(\frac{L_0 + L_3}{L_1 + L_3}\right)^F, \quad I_2 = \frac{I_1 L_1}{(L_1 + L_2)} = I_0 \left(\frac{L_0 + L_3}{L_1 + L_3}\right)^F \frac{L_1}{L_1 + L_2}.$$

Since the initial energy of the generator and the energy in the load are given by

$$W_0 = \frac{I_0^2 (L_0 + L_3)}{2} \text{ and } W_2 = \frac{I_0^2}{2} \left(\frac{L_0 + L_3}{L_1 + L_3}\right)^{2F} \frac{L_1^2 L_2}{(L_1 + L_2)^2},$$

the energy-transfer coefficient from the explosive-magnetic generator into the inductive load can be written in the form

$$k_1 = \frac{W_2}{W_0} = (L_0 + L_3)^{2F-1} \frac{L_1^2 L_2}{(L_1 + L_3)^{2F} (L_1 + L_2)^2} = \frac{(d + \beta)^{2F-1}}{(\alpha + \beta)^{2F} \left(1 + \frac{1}{\alpha}\right)^2}, \tag{2.2}$$

where $\alpha = L_1/L_2$, $\beta = L_3/L_2$, and $d = L_0/L_2$ are dimensionless parameters.

If the coefficient of perfection of the explosive-magnetic generator is $F = 0.5$ (the generator does not amplify the energy), then (2.2) reduces to Eq. (1.1), obtained for an energy-transfer coefficient into the load for steady-state inductive stores. Figure 5 shows a family of theoretical curves of $k(\alpha)$ for different values of F, representing the effect of the coefficient of perfection of the generator on the energy-transfer coefficient into the load. As the initial parameters in the calculation we took $d = 100$ and $\beta = 0.25$. The graphs of $k(\alpha)$ have a pronounced maximum, which decreases and shifts toward higher values of α as F is reduced. The greater the efficiency of operation of the explosive-magnetic generator, the less the final inductance to which the circuit must be compressed to obtain maximum energy in the load. We will optimize the energy-transfer coefficient with respect to the parameter α. To do this we differentiate (2.2) with respect to α and equate the expression obtained to zero. After solving the quadratic equation $\alpha^2 - \alpha(1/F - 1) - \beta/F = 0$ we obtain

$$\alpha_* = \frac{1 - F}{2F} + \sqrt{\left(\frac{1 - F}{2F}\right)^2 + \frac{\beta}{F}}. \tag{2.3}$$

Substituting (2.3) into (2.2), we have

$$k_* = \frac{(d + \beta)^{2F-1}}{\left[\beta + \frac{1 - F}{2F} + \sqrt{\left(\frac{1 - F}{2F}\right)^2 + \frac{\beta}{F}}\right]^{2F} \left[1 + \frac{1}{\frac{1 - F}{2F} + \sqrt{\left(\frac{1 - F}{2F}\right)^2 + \frac{\beta}{F}}}\right]^2}. \tag{2.4}$$

A family of theoretical curves of $k_*(\beta)$ for different values of F is shown in Fig. 6. The results clearly show how important the part played by the parasitic inductance of the switch is when transferring energy into the load. It is sufficient to say that whereas when $F = 1$ and $\beta = 0$ the energy-transfer coefficient $k_* = 100$, when $F = 1$ and $\beta = 0.25$ it decreases by a factor of 5.

3. Extraction of Energy from the Explosive-Magnetic Generator into an Inductive Load Taking into Account the Compression of the Magnetic Flux after the Circuit Is Broken

In the usual explosive-magnetic generator arrangement the energy is extracted into the load as follows: First, the main circuit of the generator is deformed down to a small finite inductance and the, by means of the switch, the circuit is broken and connected to the external load. As a result, a certain fraction of the stored energy from the finite inductance of the explosive-magnetic generator is transferred into the load.

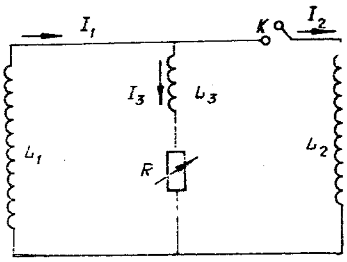

Fig. 1

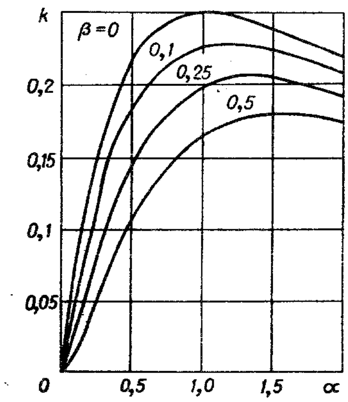

Fig. 2

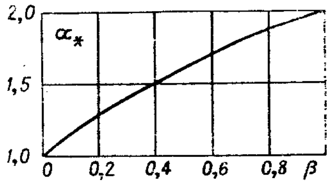

Fig. 3

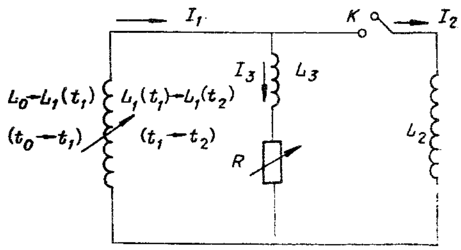

Fig. 4

Another means of extracting energy from the explosive-magnetic generator into the load is possible. It consists in breaking the circuit at an earlier period of time when the finite inductance of the deformed circuit is comparatively large. After the break, the circuit continues to deform and the magnetic flux is compressed. Unlike the first arrangement, the energy in the load here increases due to the compression of the flux. It should be noted that the increase in energy in the load due to compression of the flux after the break can only be considerable when the value of the integral $\int_0^\tau \dot{L}_1(t)\,dt$ is comparable with the value of $L_1(t_1) + L_2$, where $\dot{L}_1(t)$, where $L_1(t)$ is the rate of extraction of the inductance of the explosive-magnetic generator after the break, and τ is the assigned current pulse length in the load. We will estimate the energy possibilities of the last case and compare it with the energy-transfer circuit without flux compression.

Suppose the main circuit of the explosive-magnetic generator with initial inductance L_0 (see Fig. 4) in a time $(t_0 - t_1)$ is deformed to a final inductance $L_1(t_1)$. At the instant t_1, a load L_2 is connected to it, and the circuit, in which the resistance R increases abruptly from zero to infinity, is broken. After the break, the compression of the flux is continued and the inductance decreases to $L_1(t_2)$ in a time $(t_1 - t_2)$. If at the instant t_0 the initial flux is Φ_0, the flux Φ_1 at the instant t_1, taking the losses into account, will be

$$\Phi_1 = \Phi_0 \left(\frac{L_0 + L_3}{L_1(t_1) + L_3}\right)^{F-1},$$

while the currents in the generator and the load will be given, respectively, by the equations

$$I_1(t_1) = \frac{\Phi_1}{L_1(t_1) + L_3} = I_0 \left(\frac{L_0 + L_3}{L_1(t_1) + L_3}\right)^F,$$

$$I_2(t_1) = \frac{I_1(t_1)\, L_1(t_1)}{L_1(t_1) + L_2} = I_0 \left(\frac{L_0 + L_3}{L_1(t_1) + L_3}\right)^F \frac{L_1(t_1)}{L_1(t_1) + L_2}.$$

After the break the current in the load at the instant $t_2 > t_1$ will be

$$I_2(t_2) = I_0 \left(\frac{L_0 + L_3}{L_1(t_1) + L_3}\right)^F \frac{(L_1(t_1) + L_2)^{F-1} L_1(t_1)}{(L_1(t_2) + L_2)^F}.$$

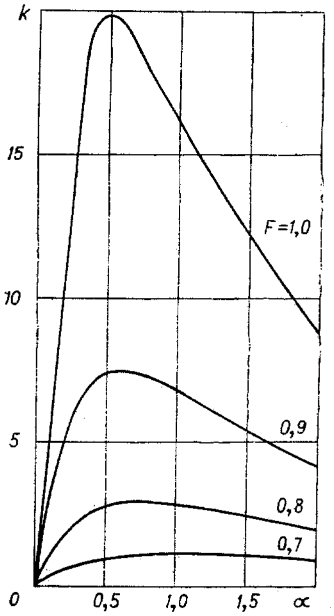

Fig. 5

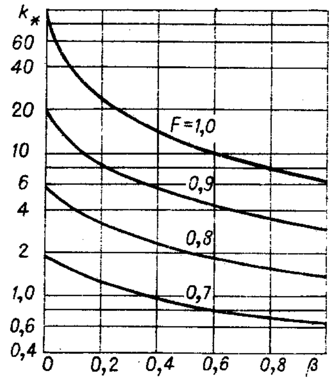

Fig. 6

The energy-transfer coefficient from the explosive-magnetic generator into the load has the form

$$k_2 = \frac{W_2}{W_0} = \frac{(L_0 + L_3)^{2F-1} L_1^2\,(t_1)\,(L_1(t_1) + L_2)^{2(F-1)} L_2}{(L_1(t_1) + L_3)^{2F}\,(L_1(t_2) + L_2)^{2F}} = \frac{(d+\beta)^{2F-1}\alpha^2(\alpha+1)^{2(F-1)}}{(\alpha+\beta)^{2F}(\mu+1)^{2F}}, \tag{3.1}$$

where $d = L_0/L_2$, $\alpha = L_1(t_1)/L_2$, $\beta = L_3/L_2$, and $\mu = L_1(t_2)/L_2$ are dimensionless quantities.

In order to establish the advantage of an explosive-magnetic generator with flux compression over the usual arrangement for extracting energy, we will compare the energy-transfer coefficients. Using Eqs. (2.2) and (3.1), we obtain

$$\frac{k_2}{k_1} = \left(\frac{\alpha+1}{\mu+1}\right)^{2F}. \tag{3.2}$$

Since $\alpha > \mu$ when $F > 0$, $k_2/k_1 > 1$. As is seen from Eq. (3.2), with respect to energy, circuits with flux compression are best for comparatively high values of α and small values of μ. This means, in practice, that the earlier the circuit is broken and the lower the value of the final inductance of the explosive-magnetic generator, the greater the energy obtained in the load.

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USE OF A PHOTOMETRIC METHOD TO MEASURE THE DISPLACEMENT OF METAL SHELLS UNDER AN EXPLOSIVE LOAD

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When measuring small displacements of a moving surface in explosive investigations the case arises when the measuring electric probes (contact, capacitive, or inductive types, etc.) cannot be placed on the surface being investigated or even in the immediate vicinity of it, for example, in experiments with strongly heated specimens, when electromagnetic interference is present, when it is necessary to preserve the measuring instruments because the loaded constructions are destroyed, etc. In such experiments one can successfully use a photometric method based on mechanical modulation of the light beam passing through a narrow slit between the surface being investigated and a fixed limiter. In [1], an experimental arrangement is described for measuring small displacements (down to 10^{-3} mm) of the surface of a cylindrical shell when it is loaded on the inside with a shock wave excited by the electrical explosion of a wire. The required light flux is obtained using a gas laser.

In this investigation the photometric method of measuring displacements was used to study the reaction of closed spherical and cylindrical shells when charges of explosive material were exploded inside them. The displacements of the shells in these experiments reached 150 μm, and the recording time was 400 μsec. The arrangement for carrying out the experiments is shown in Fig. 1. A light beam in the gap between the shell being investigated 1 and a fixed wedge 2 was produced by means of an OKG-11 helium–neon laser 9 and a rectangular diaphragm 3 placed in front of the shell. After passing across the gap, the light beam falls on an FÉU-28 photomultiplier 4 placed at a certain distance (of the order of a meter) from the shell being investigated. To eliminate the effect of external illumination on the output current, the photomultipliers were placed in a light-protecting cylindrical screen 5. Vibrations of the shell were excited by the explosion of a spherical charge 7, placed at the center of the shell. The electrical signals from the photomultiplier were recorded by an S1-18 oscilloscope 6. The calibrated dependence of the deflection of the beam on the oscilloscope screen on the value of the light gap was found using a slit placed at the position occupied by the gap, which was varied from 0.01 mm to 0.4 mm by means of a micrometer screw. The resolving power of the experimental equipment was 10^{-3} mm. The relative error in measuring the displacement was not greater than 6%.

Since the accuracy with which the light gap can be measured in this equipment, as a rule, is less than the accuracy with which the calibrated slit can be measured (due, for example, to roughness or the complex profile of the surface of the moving object, the impossibility of introducing rigid coupling between the fixed object and the movable wedge, etc.), while the laser has a time instability of its radiating power, in the measuring arrangement described in [1] additional components were introduced enabling one to make accurate measurements irrespective of the accuracy with which the gap can be displayed. To do this the light beam from the laser was divided into two parts (a transmitted beam and a reflected beam) by means of a semitransparent mirror 11 placed at an angle to the direction of the beam. The transmitted beam passed through a rectangular diaphragm and was used to measure the displacements of the loaded surface of the shell; the reflected beam was also passed through a rectangular diaphragm, then through the calibrated slit 10, and was received by the photomultiplier 8.

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