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TAKE-OFF OF ENERGY FROM EXPLOSIVE-MAGNETIC GENERATORS TO AN INDUCTIVE LOAD USING THE BREAKING OF A CIRCUIT

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The use of explosive-magnetic generators (EMG) for plasma experiments [1, 2] and for other physical investigations, along with questions of increasing the electromagnetic energy [3-9], poses the problem of the formation, in the external load, of current pulses with steep leading fronts in the microsecond range.

One method for the rapid take-off of energy to the load is the breaking of the finite circuit of the explosive-magnetic generator. This is done using commutators based on the electrical explosion of thin conductors [10-12] or on the basis of the mechanical breakdown of conductors by a charge of explosive [3, 6, 13, 14].

The efficiency of the transfer of energy to the load depends on the active resistance introduced by the commutator into the breaking circuit, and on the ratio of the inductances of the accumulator and the load. The parasitic inductance of the commutator has a great effect on the steepness of the rise of the current in the load.

The aim of the present work was a determination of the form of the pulses of the current and the energy in an inductive load as a function of the resistance of the discontinuity introduced into the circuit of an explosive-magnetic generator, taking account of the parasitic inductance of the commutating device.

1. Within the framework of an electrotechnical model, the work of an explosive-magnetic generator can be represented as the decreasing inductance L_1, connected to an explosive commutator with the parasitic inductance L_3 and the variable ohmic resistance R (Fig. 1). At the start of the compression of the magnetic flux, in an explosive-magnetic generator with the inductance L_0 there flows the current I_0. At the moment $\tau = 0$ (when the inductance of the generator has decreased to $L_1(0)$), a switch connects the load L_2 to the circuit and the commutator breaks the current in the circuit. Before the start of the discontinuity, the resistance of the commutator is equal to zero; during the discontinuity it rises according to the law $R(\tau)$ up to some final value. Taking account of the losses of the magnetic flux arising with deformation of the main circuit of the explosive-magnetic generator, the current at the moment of the start of the discontinuity, expressed in terms of the coefficient of the ideality of the system F [4], rises to the value

$$I_1(0) = I_0 \left(\frac{L_0 + L_3}{L_1(0) + L_3}\right)^F.$$

Assuming that, starting from the moment $\tau = 0$, there are no losses of the flux in the generator, in accordance with the Kirchhoff law we set up the starting system of differential equations for finding the current in the load

$$I_1\dot{L}_1 + \dot{I}_1 L_1 + \dot{I}_3 L_3 + I_3 R = 0,$$
$$I_2\dot{L}_2 + \dot{I}_2 L_2 - \dot{I}_3 L_3 - I_3 R = 0, \; I_1 = I_2 + I_3 \tag{1.1}$$

(a dot indicates the derivative with respect to the time; the parameters of the system (1.1), with the exception of L_3, the parasitic inductance of the commutator), are functions of the time).

As initial conditions we take with $\tau = 0$

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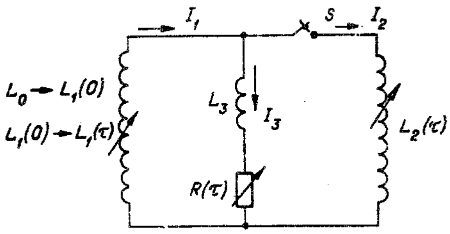

Fig. 1

$$I_1(0) = I_3(0) = I_0\left(\frac{L_0 + L_3}{L_1(0) + L_3}\right)^F, \quad I_2(0) = 0, \quad R(0) = 0.$$

After combination and integration of the first two equations of system (1.1), taking account of the initial conditions we obtain

$$I_1 L_1 + I_2 L_2 = I_1(0) L_1(0).$$

From this

$$I_1 = \frac{I_1(0) L_1(0)}{L_1} - \frac{I_2 L_2}{L_1}. \tag{1.2}$$

Substituting (1.2) into the third equation of (1.1) we obtain

$$I_3 = \frac{I_1(0) L_1(0)}{L_1} - I_2\left(1 + \frac{L_2}{L_1}\right). \tag{1.3}$$

Differentiating (1.3) with respect to the time we have

$$\dot{I}_3 = I_2\left(\frac{\dot{L}_1 L_2}{L_1^2} - \frac{\dot{L}_2}{L_1}\right) - \dot{I}_2\left(1 + \frac{L_2}{L_1}\right) - I_1(0) L_1(0) \frac{\dot{L}_1}{L_1^2}. \tag{1.4}$$

Substituting (1.3), (1.4) into the second equation of (1.1) we obtain a differential equation of the first order with variable coefficients with respect to the current in the load

$$\dot{I}_2\left[L_2 + L_3\left(1 + \frac{L_2}{L_1}\right)\right] + I_2\left[\dot{L}_2 - L_3\left(\frac{\dot{L}_1 L_2}{L_1^2} - \frac{\dot{L}_2}{L_1}\right) + R\left(1 + \frac{L_2}{L_1}\right)\right] + I_1(0) L_1(0)\left(\frac{\dot{L}_1 L_3}{L_1^2} - \frac{R}{L_1}\right) = 0.$$

We introduce the notation:

$$I_2(\tau)/I_0 = i_2;\ L_0/L_2(0) = d;\ L_1(0)/L_2(0) = \alpha_0;$$
$$L_1(\tau)/L_2(0) = \alpha;\ \dot{L}_1(\tau)/L_2(0) = \omega_1;\ L_2(\tau)/L_2(0) = \beta;$$

$\dot{L}_2(\tau)/L_2(0) = \omega_2$; $R(\tau)/L_2(0) = \rho$; $L_3/L_2(0) = \varepsilon$; $L_1(0)$ and $L_2(0)$ are the inductances of the explosive-magnetic generator and the load at the moment of the start of breakaway ($\tau = 0$).

In the new notation the solution of the equation has the form

$$i_2 = \alpha_0\left(\frac{d + \varepsilon}{\alpha_0 + \varepsilon}\right)^F \exp\left(-\int_0^\tau P(\tau)\,d\tau\right)\left[\int_0^\tau Q(\tau)\exp\left(\int_0^\tau P(\tau)\,d\tau\right)d\tau\right]. \tag{1.5}$$

where

$$P(\tau) = \frac{\frac{\omega_2}{\beta} - \frac{\varepsilon}{\alpha}\left(\frac{\omega_1}{\alpha} - \frac{\omega_2}{\beta}\right) + \rho\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)}{1 + \frac{\varepsilon}{\alpha} + \frac{\varepsilon}{\beta}}; \qquad Q(\tau) = \frac{\frac{1}{\alpha}\left(\frac{\rho}{\beta} - \frac{\omega_1}{\alpha}\frac{\varepsilon}{\beta}\right)}{1 + \frac{\varepsilon}{\alpha} + \frac{\varepsilon}{\beta}}.$$

2. Let us find the effect of the resistance of the discontinuity on the form of the current and the energy in a constant inductive load $L_2(0)$ with a given final inductance of the explosive-magnetic generator $L_1(0)$.

As experiments show, with the breaking of real circuits of explosive-magnetic generators, the resistance R does not increase instantaneously to a maximal value, but over the course of a certain interval of time. With the aim of evaluating the effect of R on the front of the rise in the current and the energy in the load, various laws are given for the resistance introduced into the circuit. For this, we shall assume that, starting from the moment of the start of the discontinuity, the resistance rises in accordance with a power law of the form $R/R_0 = (\tau/\tau_k)^n$, where R_0 is a constant ohmic resistance; n is a power exponent; τ_k is a fixed moment of time, up to which the process is considered.

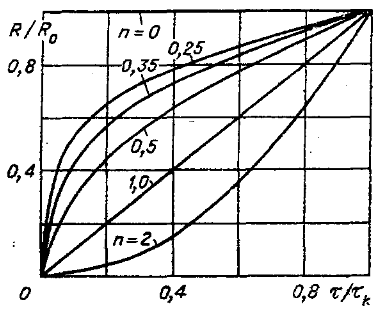

Fig. 2

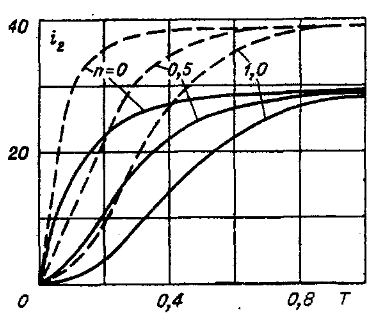

Fig. 3

Varying the exponent n, we can plot a family of curves of $R(\tau)$ with different slopes, starting from the zero point and attaining the values R_0 at the moment $\tau = \tau_k$, regardless of the value of the exponent n.

The dependences of the resistance on the time are given in Fig. 2 in dimensionless coordinates for different values of n. In the limiting case where $n = 0$, the curve reverts to a stepwise function.

The calculating formula (1.5) for the current in the load with a power law of the rise in the resistance, taking account of the coefficient of ideality F of the system of the explosive-magnetic generator, and with the condition that the final inductances of the generator and the load remain constant during the breakaway process ($\omega_1 = \omega_2 = 0$), is simplified and assumes the form

$$i_2 = \left(\frac{d+\varepsilon}{\alpha_0+\varepsilon}\right)^F \frac{1}{\left(1+\frac{1}{\alpha_0}\right)}\left[1-\exp\left(-\frac{\rho_0\tau_k}{(n+1)}\frac{T^{n+1}}{\left(\varepsilon-\frac{1}{1+\frac{1}{\alpha_0}}\right)}\right)\right], \tag{2.1}$$

where $T = \tau/\tau_k$; $\rho_0 = R_0/L_2(0)$; $0 \le T \le 1$; the coefficient of the transmission of energy from the explosive-magnetic generator to an inductive load is written in the form

$$k_2 = \frac{W_2}{W_0} = \frac{(d+\varepsilon)^{2F-1}}{(\alpha_0+\varepsilon)^{2F}\left(1+\frac{1}{\alpha_0}\right)^2}\left[1-\exp\left(-\frac{\rho_0\tau_k T^{n+1}}{(n+1)\left(\varepsilon+\frac{1}{1+\frac{1}{\alpha_0}}\right)}\right)\right]^2. \tag{2.2}$$

Expression (2.2) is the product of two factors. The first of them determines the limiting coefficient of the transmission of energy to the load, to which this quantity tends in the case of an ideal breaking of the circuit (i.e., with $\rho_0 \to \infty$). In itself, this term depends to a considerable extent on the parameter α_0 and attains a maximal value when the following condition is observed between the inductances of the circuits and the coefficient of the ideality of the explosive-magnetic generator:

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

In other words, this condition makes it possible to establish the moment of the start of the breaking of the circuit of the explosive-magnetic generator and, correspondingly, the final value of the inductance, to which the system must be deformed in order to obtain a maximal possible energy in the load.

The second factor determines the course of the rise in the current and the energy in the load and depends mainly on how the disconnection of the circuit with time takes place. The less the breaking time of the circuit and the greater the ratio $R_0/L_2(0)$, the steeper the rise of the current and the energy in the load.

The parasitic inductance of the breaker, depending on the constructional special characteristics of the breaking device itself, on the contrary, prolongs the time of the rise and leads to a lowering of the overall efficiency of the generator.

As a concrete example, let us make a quantitative evaluation of the effect of the resistance of the discontinuity and the parasitic inductance of the commutator on the process of the formation of pulses of the current and the energy in the load.

For the calculations, we take an explosive-magnetic generator with the folowing parameters:

$$d = 100;\ F = 0.9;\ \rho_0\tau_k = 5;\ \varepsilon = 0.25 \text{ and } \alpha_* = 0.53.$$

Graphical dependences of $i_2(T)$ and $k_2(T)$ are given in Figs. 3 and 4 for different values of n. For purposes of comparison, curves with $\varepsilon = 0$ are plotted with dotted lines; it can be seen that the resistance of the

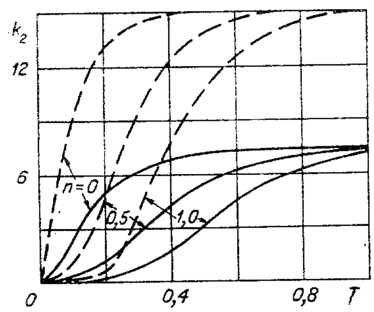

Fig. 4

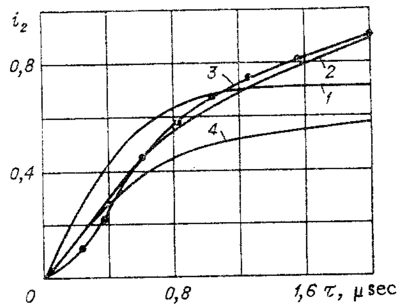

Fig. 5

discontinuity and the parasitic inductance of the commutator have a great effect on the process of the transmission of energy to the load. It is sufficient to say that while, with $n=1$ and $\varepsilon=0$, $k_2=15$, with $\varepsilon=0.25$, the coefficient of the transmission of energy decreases by almost 2 times.

It can also be noted that, with the introduction of a resistance jumpwise ($n=0$) and a small inductance of the commutator ($\varepsilon \ll \alpha$), where $\alpha=1$, the power exponent becomes equal to $2R_0\tau/L_2(0)$ and the characteristic time of the rise of the current and the energy is determined only by the ratio of the inductance of the load to the value of the resistance introduced R_0.

3. The use of thin foils in the commutators, with the aim of a rapid breaking of the circuit, and of obtaining pulses of the current with a steep front in the load imposes a definite limitation on the form and the value of the current in the explosive-magnetic generator itself. The requirement for the current of the explosive-magnetic generator is that, at the moment of the start of the discontinuity, the resistance of the foil must increase only inconsiderably due to heating; the foil itself must remain in a solid state and a criterion in accordance with which the definite integral of the action of the current must not exceed a given value (e.g., for aluminum $\sim 3\text{-}10^8\ A^2\cdot cm^{-4}\cdot sec$, and for copper $9\text{-}10^8 A^2\cdot cm^{-4}\cdot sec$ [6]) must be satisfied. The above requirement can be satisfied by the selection of determined working conditions of the explosive-magnetic generator. To decrease the integral of the action of the current, the electrical circuit must be broken at the earliest moment of time, when the final inductance of the explosive-magnetic generator is comparatively great and, after the start of the break, further deformation of the circuit is assured. It is clear that, the greater the rate of compression of the flux, the more efficient will be the transfer of energy to the load.

Let us compare the currents in the load for schemes of explosive-magnetic generators, working under conditions with compression of the flux and without compression of the flux, and analyze the advantages and shortcomings of each scheme.

With the condition that in both schemes the resistance of the discontinuity rises in accordance with a power law with a power exponent $n=0.25$ (with such an exponent and $R_0=0.05\ \Omega$, in the interval of time from zero to $\tau_k=2\cdot 10^{-6}$ sec, the calculated value of $R(\tau)$ for the chosen construction of the commutator approximates well the experimental curve of the resistance); in the scheme of an explosive-magnetic generator with compression of the flux, from the moment of the start of the break the inductance decreases with time according to a linear law with a constant rate $\dot{L}_1$(i.e., $\alpha=\alpha_0-\omega_1\tau$). The choice of a linear dependence of the inductance is not the result of change: It gives a sufficiently good description of the real curve of the inductance of the explosive-magnetic system of the given class.

Using formulas (1.5) and (2.1), let us make a numerical calculation of the currents in an inductive load.

As the starting data in the scheme of an explosive-magnetic generator without compression of the flux we take $L_2(0)=18$ nH; $\tau_k=2\cdot 10^{-6}$ sec; $R_0=0.05\ \Omega$; $F=1.0$; $d=1.4$; $\varepsilon=0.28$; $\rho_0\tau_1\simeq 5.5$; $\alpha_0=0.56$.

In a scheme with compression of the flux $L_2(0)=18$ nH; $\tau_k=2\cdot 10^{-6}$ sec; $R_0=0.05\ \Omega$; $\omega_1=0.41\cdot 10^6\ sec^{-1}$; $F=1.0$; $d=1.4$; $\varepsilon=0.28$; $\rho_0\tau_k=5.5$; $\alpha_0=1.4$ (here the breaking of the circuit takes place at a time τ_k, earlier than in the scheme without compression of the flux; with an increase in the time, the parameter α decreases and, at the end of the process, due to the selection of ω_1, attains a value equal to the value of α_0 for the first scheme).

The results of calculations of $i_2(\tau)$ are given in Fig. 5 (curve 1 relates to a scheme of an explosive-magnetic generator with compression of the flux, and curve 2, with compression of the flux).

Two characteristic special features can be observed in the behavior of the curves. One of them consists in the fact that, in the first scheme of an explosive-magnetic generator, the front of the rise of the current in the first stage of the process is steeper than in the scheme with compression of the flux. Another special characteristic relates to the final values of the currents: after the point of intersection, the curves diverge considerably, and each of them tends toward its own limiting value. With respect to the value of the current, the scheme with compression of the flux has a distinct advantage here.

The work of an explosive-magnetic generator with compression of the flux was verified experimentally (curve 3). The satisfactory agreement between calculation and experiment bears witness to the correctness of our assumptions in the derivation of the calculating formulas.

For purposes of comparison, Fig. 5 plots the calculated curve 4 for the scheme of an explosive-magnetic generator with compression of the flux in the case where the inductance of the load after the start of the break rises linearly at a rate equal to the rate of decrease in the inductance of the main circuit ($\omega_1 = \omega_2$), i.e., $\beta = 1 + \omega_2 \tau$. Although the form of the curve of $i_2(\tau)$ practically does not differ from those considered earlier, however, the rise in the load inductance considerably lowers the amplitude of the current and, in the given example, its value at the moment $\tau = \tau_2$ decreases by practically 1.5 times.

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