CHARGING OF AN INDUCTIVE ACCUMULATOR FROM AN EXPLOSIVE-TYPE MAGNETIC GENERATOR THROUGH AN ELECTRICAL EXPLOSIVE-TYPE CURRENT BREAKER

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Analytical investigations were made of electromagnetic processes with the work of an explosive-type magnetic generator, in a series-connected inductive-type accumulator and a current breaker based on an exploding wire. A solution is obtained in dimensionless form for a model of a current breaker based on an ohmic resistance, whose value rises linearly with the temperature. The conditions are determined under which an inductive load can be connected in parallel to the current breaker; under these circumstances, the current of the load branch remains small during the whole charging stage.

Explosive-type magnetic generators are the most powerful sources of pulsed currents. Their use in experimental physics is frequently limited by the relatively large compression time of the magnetic flux [1]. To eliminate this shortcoming, the circuit for the connection of an explosive-type generator illustrated in Fig. 1a has been proposed and verified experimentally [1, 2].

Here 1 is the explosive; 2 is a liner; 3 is a cassette; 4 is a spark gap; 5 is an electrical explosive-type current breaker; 6 is a load solenoid. During the compression of the magnetic flux, the load is disconnected, and the accumulation of energy takes place in the inductance of the connections. At the end of the process of the collapse of the liner, there is an electrical explosion of the wire, its resistance rises sharply, and the voltage pulse formed breaks down the spark gap. After a short time, the energy from the inductive accumulator is transmitted to the load. To simplify the analysis, we shall not take account of the parasitic parameters of the circuit: the ohmic resistances of the generator, the connections, and the load solenoid, as well as the inductance of the current breaker. Then the circuit takes on the form of Fig. 1b, where the following notation is used: L_1 is the inductance of the generator; L_2 is the inductance of the accumulator; R is the resistance of the current breaker; L_3 is the inductance of the load.

It is usually assumed [3, 4] that the first stage in the work of a current breaker is its heating up to the boiling point, while the second stage is the breaking of the current as the result of a sharp rise in the resistance during the process of explosive vaporization.

Since the duration of the second stage is much less than that of the first stage, conditions close to optimal will be achieved if the boiling point of the current breaker is reached at the moment of the total collapse of the liner. In accordance with this, we assume that for a period of time T determined by the length of the generator and the detonation rate, there is compression of the flux and heating of the current breaker up to the boiling point; here the load L_3 is disconnected. The electrical circuit of Fig. 1b will be described by

$$\frac{d(LI)}{dt} + RI = 0 \tag{1}$$

$$\frac{dR}{dt} = \frac{\alpha R_0}{c_p m_0} RI^2, \quad L = L_1(t) + L_2 \tag{2}$$

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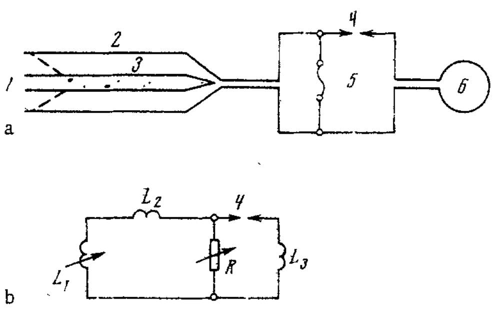

Fig. 1

where R_0, m_0 are the initial values of the resistance and mass of the current breaker; α, c_p, are the temperature coefficient of the resistance and the specific heat capacity of the material.

The quantities α and c_p are functions of the temperature. We shall use the mean value of the coefficient of thermal resistance $\beta = \alpha/c_p$ in the range from room temperature to the boiling point. This coefficient must be determined from the experimentally found dependence

$$R = R_0\left(1 + \beta\frac{Q}{m_0}\right)$$

where Q is the energy absorbed by the wire.

Questions of the effective use of explosives and the optimal layout of busbars are discussed in [5]. The present article discusses the problem of the compatibility of the parameters of the generator and the current breaker from the condition of an electrical explosion at the end of the cycle $R(T) = R_c$, where R_c is the resistance at the boiling point. The layout is given, i.e., busbars of constant width. We then obtain

$$L = L_0\left(1 - \frac{1 - 1/\eta}{T}t\right), \qquad L_0 = L_1(0) + L_2 \tag{3}$$

where $\eta = L_0/L_2$ is the tuning coefficient.

We eliminate I from the system of equations (1), (2), for which purpose we write (1) in the form

$$\frac{1}{2}\int_0^t I^2 dL + \int_0^t RI^2 dt + \frac{1}{2}LI^2 - \frac{1}{2}L_0I_0^2 = 0$$

and, substituting the values of the integrals found from (2), (3), we obtain

$$-\frac{m_0L_0(1-1/\eta)}{2\beta R_0 T}\ln\frac{R}{R_0} - \frac{m_0}{\beta}\left(\frac{R}{R_0} - 1\right) + \frac{L_0 m_0}{2\beta R_0}\left(1 - \frac{1-1/\eta}{T}t\right)\frac{1}{R}\frac{dR}{dt} - \frac{L_0I_0^2}{2} = 0 .$$

We introduce the dimensionless quantities

$$\ln\frac{R}{R_0} = y, \quad \frac{L_0}{R_0T} = \tau_0, \quad \frac{t}{T} = x, \quad \frac{L}{L_0} = l, \quad \frac{R_c}{R_0} = r_c, \quad \frac{I}{I_0} = i$$
$$a = \frac{\tau_0}{2}(1 - 1/\eta), \qquad b = \frac{\beta L_0 J_0^2}{2m_0} .$$

Substituting them into the last equality, we find

$$ay - e^y + 1 - \frac{\tau_0}{2}[1 - (1 - 1/\eta)x]\frac{dy}{dx} + b = 0 \tag{4}$$

or in integral form

$$-\frac{1}{a}\ln l = \int_0^y \frac{dy}{1 + b + ay - \exp y} .$$

The integral in the right-hand part is not expressed in elementary functions and must be determined numerically. With $x = 1$, $y = \ln r_c$, $l = 1/\eta$, and the condition for explosion at the end of a cycle assumes the form

$$\eta = \exp a \int_0^{\ln r_c} \frac{dy}{1 + b + ay - \exp y} . \tag{5}$$

The quantity r_c is a physical constant of the material of the current breaker. In accordance with [1], we have for Al, $r_c = 15$, and for Cu, $r_c = 20$. It can be seen from Eq. (4) that the boiling point is not reached with any values of a and b, but only at values which satisfy the condition

$$1 + b + a\ln r_c - r_c \geqslant 0 \tag{6}$$

since, otherwise, dy/dx reverts to zero at some value of $t < T$, i.e., the resistance of the current breaker ceases to rise before the value R_c is reached.

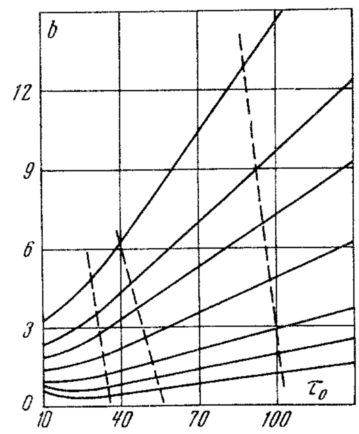

Fig. 2

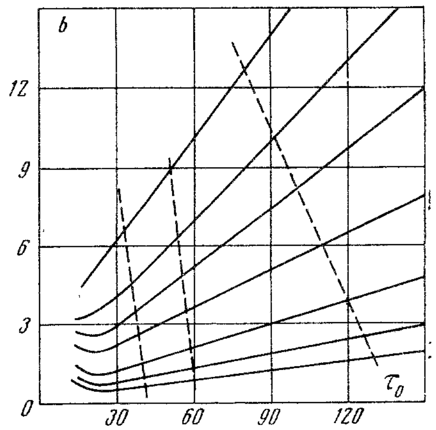

Fig. 3

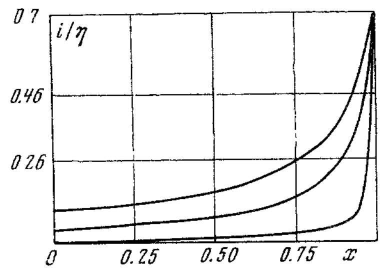

Fig. 4

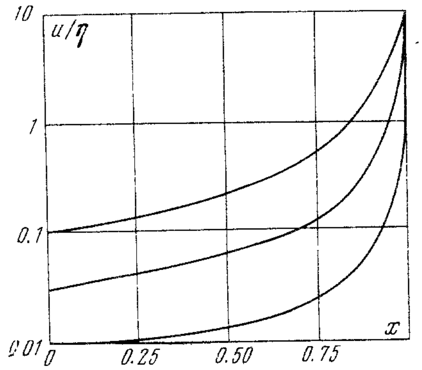

Fig. 5

Each pair of values of a and b satisfying (6) corresponds to a value of η determined by condition (5). Thus, a connection is established between τ_0, b, and η. These dependences for Al and Cu, plotted using an electronic computer, are shown, respectively, in Figs. 2 and 3. It can be seen that with sufficiently large values of τ_0 and fixed values of η the dependences of b on τ_0 are linear.

Let us calculate the coefficient of conservation of the magnetic flux:

$$k = \frac{I(T)\,L(T)}{I_0 L_0} = \frac{i(1)}{\eta} \ .$$

Setting x = 1, y = ln r_c in Eq. (4), and taking into account that

$$\frac{dy}{dx} = T\,\frac{dy}{dt} = \frac{3R_0 T}{m_0}\,I^2$$

we find

$$k^2 = \frac{1 + b + a \ln r_c - r_c}{\eta b} \ . \tag{7}$$

The value of k^2 determines the magnetic energy

$$Q_2 = k^2\,\frac{(I_0 L_0)^2}{2L_2}$$

stored in the inductive accumulator after actuation of the generator. τ_0, b, and η must be so selected that k will be as close as possible to unity. Fixing the values of k^2 and η in expression (7), we obtain a dependence between b and τ_0. The curve of this dependence intersects the corresponding straight line (Figs. 2, 3) at a point which ensures a given coefficient of conservation of the momentum of the flux at the end of a cycle of the explosive-type magnetic generator.

These points are connected by the dotted curves in Figs. 2, 3. It can be seen from the figures that the working range of τ_0 for Al is 30-100 and for Cu, 30-130. An increase in the value of τ_0 above the upper limit does not lead to a rise in k, since, in this case, the losses of energy will be determined by other factors, which are not taken into account here (for example, the sliding contacts of the liner). A decrease in the value of τ_0 below the lower limit leads to a situation in which more than half of the energy evolved by the explosive-type magnetic generator is absorbed by the current breaker.

The solution obtained permits an exact determination of the state of the system at only one point, i.e., at the end of the first stage, $r(1) = r_c$, $i(1) = k\eta$, where k is determined by the equality (7). These data are sufficient for calculation of the second stage, i.e., the current breaker; however, the course of the process during the period of time $0 \leq t \leq T$ is of definite interest, i.e., the form of the current and voltage pulses in the current breaker. Simple approximate expressions can be obtained for $i(x)$, $r(x)$, and $u(x) = i(x)r(x)$. Bearing in mind that the damping of the magnetic flux takes place gradually with time, from I_0L_0 to kI_0L_0, we obtain an evaluation for the current:

$$k/l < i < 1/l.$$

Here $i(0) = 1$, $i(1) = k\eta$.

Assuming uniform damping of the flux with time, we obtain

$$i \cong \frac{1-(1-k)x}{1-(1-1/\eta)x}. \qquad (8)$$

From Eq. (2) it follows that

$$\ln r = \frac{3R_0I_0^2T}{m_0}\int_0^x i^2 dx.$$

Neglecting the damping of the flux, i.e., assuming

$$k = 1, \; i = 1/l$$

we have

$$\ln r \cong \frac{3R_0I_0^2T(1/l-1)}{m_0(1-1/\eta)} = \frac{2b(1/l-1)}{\tau_0(1-1/\eta)}.$$

Out of this there flows an approximate condition for explosion at the end of a cycle for k = 1

$$2b\,\eta/\tau_0 \ln r_c \cong 1. \qquad (9)$$

If $k \neq 1$, then, taking account of the evaluation for i, we can write the following evaluation for r:

$$ck^2\int_0^x \frac{dx}{l^2} < \ln r < c\int_0^x \frac{dx}{l^2}$$

where c is an as yet undetermined coefficient of proportionality. Replacing k by a linearly decreasing function [analogous to (8)], and determining c from the condition $r(1) = r_c$, we obtain the approximate equality

$$r \cong \exp[1-(1-k)x]^2\left[\frac{1}{1-(1-1/\eta)x} - 1\right]\frac{\ln r_c}{k^2(\eta-1)}. \qquad (10)$$

Dependences of $i(x)$ and $u(x)$ for Al are shown in Figs. 4, 5.

Let us consider a modification of the circuit of Fig. 1b (the load L_3 is connected to the current breaker, and the spark gap 4 is eliminated). With a sufficiently large value of L_3, the current of the load branch in the first stage is small, the circuit of the unit is simplified, and energy losses in the spark gap are eliminated. If $I_3 \ll I$, then $L_3(dI_3/dt) = IR$, whence

$$i_3 = -\frac{R_0T}{(1-1/\eta)L_3}\int_1^l ir\,dl.$$

Neglecting the damping of the flux, i.e., assuming k = 1, we obtain

$$i_3(x) = \frac{R_0T\exp(-\ln r_c/(\eta-1))}{L_3(1-1/\eta)}\left[E_i^*\left(\ln r + \frac{\ln r_c}{\eta-1}\right) - E_i^*\left(\frac{\ln r_c}{\eta-1}\right)\right]$$

where $E_i^*(x) = \int_{-\infty}^{x}(e^t/t)\,dt$ is an integral indicating function, tabulated, for example, in [6].

With $x=1$ and $10 \leq \eta \leq 100$, the quantity in square brackets varies in the range 10.3-12.8. It can be set equal to 10; if, in addition, it is taken into consideration that

$$\exp\left[-\ln r_c / (\eta - 1)\right] \approx 1$$

and if the value of $1/\eta$ is neglected in comparison with unity, we then obtain

$$i_3(1) \cong 10 \frac{R_0 T}{L_3} .$$

The condition with which it is possible to connect the inductive load directly in parallel with the current breaker assumes the form

$$\iota(1)/i_3(1) \cong \eta L_3 / 10 R_0 T \gg 1 . \quad (11)$$

Thus, the electromagnetic processes with the charging of an inductive accumulator from an explosive-type magnetic generator through a current breaker are determined by three dimensionless parameters ($\tau_0 = L_0/R_0T$, $b = \beta L_0 I_0^2/2m_0/\ 2m_0$, $\eta = L_0/L_3$) and the dimensionless time ($x = t/T$).

The condition for the achievement of the boiling point of the current breaker at the end of a cycle of the explosive-type magnetic generator connects the parameters τ_0, b, and η by a dependence which, with fixed values of η and sufficiently large values of τ_0, is linear (Figs. 2, 3).

The working range of the parameters τ_0 and b lies in the region of values $b = 0.5$-13, $\tau_0 = 30$-100 for Al, $\tau_0 = 30$-130 for Cu.

With the condition $\eta L_3 \gg 10 R_0 T$, the inductive load can be connected directly in parallel with the current breaker.

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