ENERGY TRANSFER FROM AN INDUCTIVE STORAGE TO AN INDUCTIVE LOAD BY MEANS OF AN EXPLOSIVE CURRENT DISCONNECT

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A study is made of switching of current from an inductive storage by electrical explosion of a wire shunting an inductance in conformity with a model based on surface vaporization waves. It is established that the nature of the process is determined by certain generalized dimensionless parameters of the system. The modes of most efficient transfer of energy to the load are determined.

The diagram in Fig. 1 corresponds to the completion of charging of an inductive storage from an external energy source and to the beginning of the process of energy transfer from the storage to a load. If the initial conditions are known, the final state of the system (after cutoff of the current in the branch R) is determined directly from the laws for the conservation of energy and magnetic flux [1]. However, the very nature of the switching process remains unknown. This process is considered here in conformity with the model of a current disconnect based on the concept of surface vaporization waves during electrical explosion of a wire [2]. Since the abrupt rise in the resistance of an exploding wire begins in the boiling stage, we take as initial conditions when $t=0$ and $R=R_b$ (resistance of the disconnect at the boiling point), $I_L=0$, $I=I_d=I_0$ (it is assumed the discharge gap closes the load branch at $t=0$). If the initial mass of the disconnect is m_0 and the energy of the electrical explosion per unit mass is q, then, assuming the metal vapor is nonconducting, we obtain for the resistance of the disconnect

$$R=\frac{R_b}{1-\frac{Q_d}{m_0 q}}, \tag{1}$$

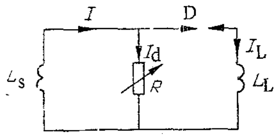

Fig. 1

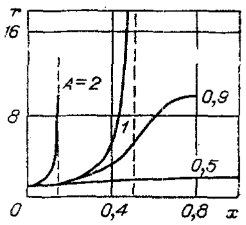

Fig. 2

where Q_d is the Joule heat deposited in the disconnect from the time $t=0$. It should be noted that it is necessary to determine the quantity q experimentally, since it may be two to three times greater than the latent heat of vaporization under normal conditions during very fast explosions [3]. The circuit in Fig. 1 is described by the system of differential equations

$$L_s\frac{dI}{dt}+RI_d=0,$$

$$L_s\frac{dI}{dt}+L_L\frac{dI_L}{dt}=0,$$

$$I=I_d+I_L.$$

We then find the relations characterizing the process of current cutoff,

$$I_d=I_0\exp-\int_0^t\frac{R(t)}{L_e}dt, \tag{2}$$

$$Q_d=Q_0\frac{L_L}{L_s+L_L}\left[1-\left(\frac{I_d}{I_0}\right)^2\right], \tag{3}$$

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$$Q_L = Q_0 \frac{L_s\ L_L}{(L_s + L_L)^2}\left[1 - \frac{I_d}{I_0}\right]^2. \tag{4}$$

Here Q_L is the value of the energy transferred to the load, $Q_0 = \frac{1}{2} L_S I_0^2$ is the initial energy in the storage, and $L_e = L_S L_L/(L_S + L_L)$ is the equivalent inductance of the circuit (with respect to the disconnect).

Equations (2)-(4) make it possible to determine the efficiency of energy transfer for incomplete disconnection where $I_d \neq 0$, and they transform into well-known equations when $I_d = 0$ [1]. We calculate the current and voltage in the load. In our case, the relation R(t) is not given, and therefore it is impossible to use Eq. (2) directly. We write it in the form

$$\frac{1}{2} L_e \frac{dI_d^2}{dt} + RI_d^2 = 0 \tag{5}$$

and add an equation which is obtained by differentiation of Eq. (1),

$$\frac{dR}{dt} = \frac{1}{m_0 q R_b} R^3 I_d^2. \tag{6}$$

Eliminating I_d from the equation system (5), (6), we obtain

$$R\frac{d^2R}{dt^2} - 3\left(\frac{dR}{dt}\right)^2 + \frac{2}{L_e} R^2 \frac{dR}{dt} = 0.$$

This equation permits a reduction in order and is solved in the form

$$\frac{dR}{dt} = \left(\frac{I_0^2}{m_0 q R_b} - \frac{2}{L_e R_b} + \frac{2}{L_e R}\right) R^3, \tag{7}$$

(here the constant of integration is determined from the initial conditions). For the subsequent analysis, it is convenient to introduce the dimensionless quantities

$$x = \frac{R_b t}{L_e};\ r = \frac{R}{R_b};\ i_d = \frac{I_d}{I_0}\ \ i_L = \frac{I_L}{I_0};\ u = \frac{I_d R}{I_0 R_b};\ A = \frac{L_e I_0^2}{2m_0 q}.$$

Integration of Eq. (7) gives for the resistance

$$x = \frac{1}{2}\left[1 - \frac{1}{r} + (A-1)\ln\left(1 - \frac{1-\frac{1}{r}}{A}\right)\right], \tag{8}$$

and after substitution of Eq. (7) into Eq. (6), we find

$$i_d = \sqrt{1 - \frac{1}{A}\left(1 - \frac{1}{r}\right)}, \tag{9}$$

$$u = r\sqrt{1 - \frac{1}{A}\left(1 - \frac{1}{r}\right)}. \tag{10}$$

The current in the load is easily determined from the conservation of magnetic flux in the storage–load circuit

$$i_L = i_{st}\left[1 - \sqrt{1 - \frac{1}{A}\left(1 - \frac{1}{r}\right)}\right], \tag{11}$$

where $i_{st} = 1/[1 + (L_L/L_S)]$ is the stabilized value of the current in the circuit (after cutoff of the current in the disconnect circuit).

We now consider three particular cases separately.

1. Low-energy mode, $A = L_e I_0^2/2m_0 q < 1$.

In this case, complete vaporization of the disconnect does not occur and the variation in current, resistance, and voltage does not have the nature of an explosion. In fact, it is clear from Eq. (8) that the quantity r is bounded for any x. The maximum value r_M which is reached in this mode when $x \to \infty$ is determined from

$$\frac{1 - \frac{1}{r_M}}{A} = 1; \qquad r_M = \frac{1}{1-A}.$$

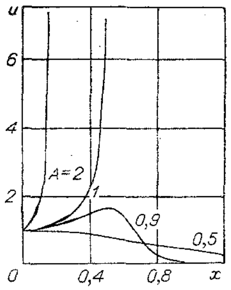

Fig. 3

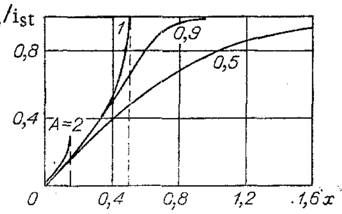

Fig. 4

Figures 2-4 show r(x), u(x), and $i_L(x)/i_{st}$ plotted in accordance with Eqs. (8), (10), and (11). For $A < 1$, all three quantities reach their stabilized values when $x \to \infty$, i.e., asymptotically.

2. High-energy mode, $A > 1$.

The resistance of the disconnect goes to infinity after a finite explosion time.

$$r \to \infty \text{ when } x \to x_{ex} = \frac{1}{2}\left[1 + (A-1)\ln\left(1 - \frac{1}{A}\right)\right]. \tag{12}$$

At this time, the current in the disconnect differs from zero

$$x = x_{ex}, \quad i_d = \sqrt{1 - \frac{1}{A}},$$

and, consequently, the voltage on it goes to infinity, $u \to \infty$ when $x \to x_{ex}$. Physically, this means that electrical explosion of a wire does not lead in this case to current cutoff in this branch. Because of the overvoltage (theoretically infinitely great), there should occur a breakdown of the gap which is formed after explosion of the disconnect. We point out that it is impossible to avoid this breakdown by any means because one of the conservation principles (for energy or for magnetic flux) would otherwise be violated. The current in the discharge channel will flow until the total energy absorbed in this branch from the time $t = 0$ reaches the value defined by Eq. (3). Following this, the discharge is quenched regardless of the value of the resistance in the discharge channel. The nature of the variation of resistance, current, and voltage in the disconnect branch after breakdown of the gap is determined by the specific discharge conditions. The duration of the electrical explosion, x_{ex}, decreases with increase in the parameter A for

$$A \gg 1 \quad x_{ex} \cong \frac{1}{4A}, \quad i_d \cong 1 - \frac{1}{2A}; \quad i_L = \frac{i_{st}}{2A}.$$

As A increases, x_{ex} decreases and the switching becomes poorer (the disconnect current i_d cannot be reduced significantly after the time t_{ex} and the load current i_L cannot be increased). The main part of the switching process is accomplished in an uncontrolled fashion after breakdown of the gap. The curves r(x), $i_L(x)$, and u(x) for $A = 2$ are shown in Figs. 2, 3, and 4.

3. Critical mode, $A = 1$.

In this case, Eqs. (8)-(11) are considerably simplified:

$$r = \frac{1}{1-2x}; \quad i_d = \sqrt{1-2x}; \quad u = \frac{1}{\sqrt{1-2x}}; \quad i_L = i_{st}\left(1 - \sqrt{1-2x}\right).$$

The quantity r goes to infinity for $x_{ex} = 1/2$. Then $i_d = 0$, $u \to \infty$. This means the electrical explosion of the disconnect is either completely unaccompanied by breakdown of the gap (if the discharge cannot be formed during the short time in which the overvoltage pulse is effective) or a breakdown is started but the discharge current is very low and dies out quickly.

In conclusion, we turn to the question of the limits of applicability of the surface vaporization model assumed. The problem is rather complex and requires special consideration. However, it is clear from Eq. (12) that the time x_{ex} can become as small as desired through an increase in A. At the same time, it is clear that the velocity of the surface vaporization wave front (v) is finite (it cannot exceed the velocity of sound in liquid metal) and therefore $t_{ex} = l/v$, where l is some cross-sectional dimension of the disconnect (for a wire, the radius; for a foil, the half-thickness). This inequality also determines the limit of applicability of the surface vaporization model; if A is so large that Eq. (12) is inconsistent with the inequality, then the model is inapplicable. From published data [3], the velocity v does not exceed 200 m/sec, which corresponds (for $l < 0.1$ mm) to a t_{ex} of tens and hundreds of nanoseconds. Such switching times have been observed experimentally [2, 4].

LITERATURE CITED

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