CALCULATING SCHEME AND SWITCHING-ON OF THE LOAD OF PLANE EXPLOSIVE-DRIVEN MAGNETIC GENERATORS

E. I. Bichenkov, A. E. Voitenko,
V. A. Lobanov, and E. P. Matochkin

UDC 621.365.91

A scheme is described for calculating explosive-driven magnetic generators, and analytical and numerical calculations are made of the problem of switching a generator on to a constant ohmic and induction load, to a load whose resistance rises linearly with the temperature, and to a plasma load with equilibrium radiation. In the latter case, a calculation is made of a variant involving switching on the load through a matched transformer.

1. The use of the energy of explosives for the rapid constriction of the magnetic flux inside a conducting circuit [1] has been put into practice in a number of constructions of explosive-driven magnetic generators [1-7], which are the most powerful generators of an electric current. An explosive-driven magnetic generator has specific electrotechnical characteristics which must be taken into account in matching it with various types of loads.

The present article discusses some calculating relationships, obtained for a plane [4], explosive-driven magnetic generator with a load of an inductive and active character. A closely allied construction of a generator was developed by Herlach and Knoepfel [5]. A plane generator (Fig. 1) consists of copper busbars (1) of varying width, a welded copper holder (2) located between the busbars, and a charge of explosive (3), filled into the internal hollow of the holder. The generator is connected by cables (5) with a condenser battery. At the moment when the discharge current attains a maximum, the percussion cap (4) is detonated, and a detonation wave is propagated along the charge of explosive. Under the action of the products of the explosion, the side walls of the holder are scattered to the sides, short-circuiting the busbars of the generator and gradually forcing the magnetic flux into the load (6). The work of explosive-driven magnetic generators is discussed in more detail in Knoepfel's book [8].

2. From an electrotechnical point of view, an explosive-driven generator is part of a circuit with a variable inductance L(t). We postulate that the busbars of the generator are parallel, that their width 2y varies slowly along the length of the generator, x, and that the distance between the busbars, 2b, is much less than the width. Denoting the total length of the generator by l, and assuming that the rate of short-circuiting of the plates is constant and equal to the rate of detonation, D, we can write the dependence of the inductance of the generator on time

$$L(t) = 4\pi b \int\limits_{-l+Dt}^{0} \frac{dx}{y(x)} \quad (2.1)$$

The origin of coordinates is located at the point of the connection between the generator and the load; the time is reckoned from the moment of short-circuiting of the generator by the explosion.

With a change in the inductance, the power developed by such a generator is equal to $2^{-1}c^{-2}I^2D(dL/dx)$. On the other hand, it is equal to some fraction k of the power $4qy\delta D$, developed with the explosion of the charge of explosive. Thus, we can write

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhanika i Tekhnicheskoi Fiziki, No. 2, pp. 37-41, March-April, 1973. Original article submitted October 25, 1972.

$$\frac{\pi b}{2c^2}\frac{I^2}{y} = kqy\delta \qquad (2.2)$$

Here I is the current in the generator; q is the energy of the explosive per unit volume; 2δ is the thickness of the layer of explosive; c is an electrodynamic constant.

In any given cross section of the generator, the coefficient k cannot exceed some maximal value, determined by the charge of explosive, the current, and the construction of the generator. A generator will work under optimal conditions if k attains this value everywhere, i.e., if it is constant along the length of the generator.

Together with conditions (2.1) and (2.2), writing the energy equation for the electrical circuit and the equations determining the resistance and the other electrotechnical parameters, we can obtain a closed system of equations, from which there are determined the cut of the busbars of the generators, y(x), the dependences of the current and the energy developed in the load on the time, and other characteristics of the generator.

3. For a circuit with an inductance of the load L_1, having a resistance R, with k = const the energy equation has the form

$$\frac{L(t)+L_1}{2c^2}I^2 + \int_0^t RI^2 dt = 4kq\delta \int_{-l}^{-l+Dt} y(x)\,dx + \frac{L_0 I_0^2}{2c^2} \qquad (3.1)$$

The initial inductance $L_0 = L(0) + L_1$.

The problem of switching an explosive-driven generator on to a constant resistance $R = R_0$ is solved analytically. The cut of the busbars of the corresponding generator is

$$y(x) = y_0 \exp\left[\frac{c^2 R_0}{L_0 D}(l+x)\left(\frac{4\pi b D}{c^2 R_0 y_0} - 1\right)\right] \qquad (y_0 = y(-l)) \qquad (3.2)$$

Here y_0 is the width of the busbars at the start of the generator.

Sometimes a generator works only on an inductive load. The corresponding cut of the busbars is obtained by passing to the limit in (3.2), $R_0 \to 0$. This case corresponds to the generator discussed in [4], in which the exponent is approximated by straight segments.

There exists a critical value of the resistance

$$R_* = 4\pi b D / c^2 y_0$$

at which the width of the busbars and the current of the generator are constant. With $R_0 < R_*$, the width of the busbars and the current of the generator increase, while with $R_0 > R_*$ they decrease. These conditions involve a strong loss of magnetic flux and, in many cases, are unsatisfactory.

The energy E developed in an ohmic load after the working time of the generator, referred to the initial energy of the magnetic field in the generator, $E_0 = L_0 I_0^2 / 2c^2$, is equal to

$$\frac{E}{E_0} = \frac{2c^2}{L_0 I_0^2}\int_0^t R_0 I^2 dt = \frac{\rho(n-1)\left[(n+1)+\rho(n-1)\right]}{\left[1+\rho(n-1)\right]^2}$$

$$(\rho = R_0 / R_*, \quad n = L_0 / L_1)$$

The maximal value of E/E_0 as a function of ρ with a given arbitrary coefficient of retuning of the generator n is equal to $(n+1)^2/4n$ and is attained at $\rho = (n+1)/(n-1)^2$. In this case, the current rises by $(n-1)/2$ times.

In the case $\rho = 1$, the current is constant, and the energy in the load, $E = 2E_0(1 - 1/n)$, exceeds the initial reserve of energy in the generator by approximately two times.

For the most important case of generators with $n \gg 1$

$$E = E_0 \rho (1+\rho) n^2 / (1+\rho n)^2 \qquad (3.3)$$

and a maximal energy is attained in the load

$$R_0 = n^{-1} R_* \qquad (3.4)$$

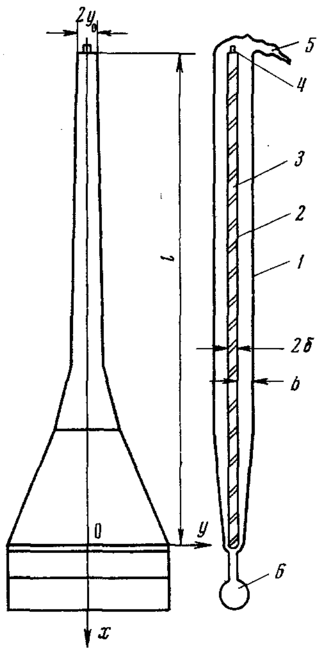

Fig. 1

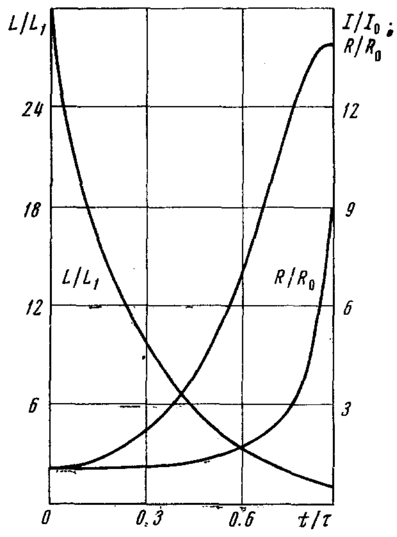

Fig. 2

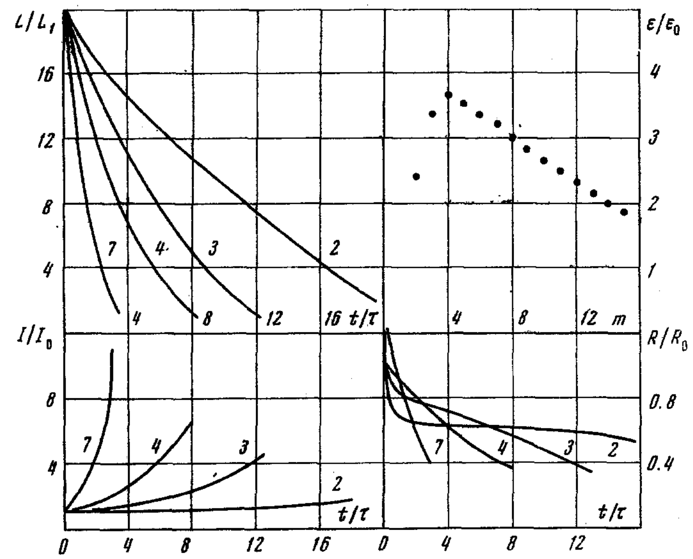

Fig. 3

For the energy of the explosive charge, we have

$$Q_0 = 4q\delta \int_{-l}^{0} y(x)\,dx = \frac{(n-1)^2}{2nk} E_0 \approx \frac{n}{2k} E_0$$

The ratio of the maximal energy in the load (3.3), under condition (3.4), to the total energy of the charge of explosive is equal to

$$E / Q_0 = k / 2$$

Thus, with $n \gg 1$, half of the energy developed by the generator goes into heat, while the second half remains in the form of the energy of the magnetic field, connected with the residual inductance of the generator.

4. The case of a resistance R(t) varying with the heating is more complicated. Assuming that the change in the resistance is proportional to the change in the temperature, we obtain

$$\frac{dR}{dt} = \frac{\alpha R_0}{\lambda} RI^2 \quad (4.1)$$

where α is the temperature coefficient of the resistance; λ is the total heat capacity of the resistor; R_0 is the initial value of the resistance.

The system of equations (2.1), (2.2), (3.1), (4.1) was solved numerically in an electronic computer using a Runge-Kutta program with automatic selection of the spacing. In dimensionless form, the solution depends on the parameters

$$A_1 = \frac{4\sqrt{\pi}D}{cR_0I_0}\sqrt{kbq\delta}, \qquad A_2 = \frac{L_0I_0^2\alpha}{c^2n\lambda}$$

The results of a calculation of the dependences L/L_1, I/I_0, and R/R_0 on the dimensionless time $\tau = c^2R_0L_1^{-1}t$ with $A_1 = 10^2$, $A_2 = 5\cdot10^{-2}$, are given in Fig. 2. The value of the current, calculated from condition (2.2), may be used to determine the width of the busbars and to design an optimal generator for a given case.

With a given value of n in a load whose resistance rises with time, more energy can be developed than in the case of a constant resistance. A variable width of the busbars increases the efficiency of the utilization of the energy of the explosion, compared to a generator with a constant width, discussed in [9].

For the efficient heating of a load with a large resistance, a matching transformer must be connected between the generator and the load. The optimal transformation coefficient with respect to the current

$$m = I / I_1 \quad (4.2)$$

is to be determined.

As an example, we consider a plasma load whose resistance decreases with a rise in the temperature

$$R = R_0 (T_0 / T)^{3/2} \quad (4.3)$$

For a dense plasma radiating as a blackbody, the energy balance in the load has the form

$$\lambda (T - T_0) + \int_0^t \sigma T^4 S dt = \frac{1}{m^2}\int_0^t RI^2 dt \quad (4.4)$$

where λ is the total heat capacity of the plasma; S is the radiating surface; σ is the Stefan–Boltzmann constant. The problem is determined by the dimensionless parameters

$$B_1 = \frac{4\pi bD}{c^2y_0R_0}m^2, \quad B_2 = \frac{3\sigma T_0^3SL_1}{2\lambda c^3R_0}m^2, \quad B_3 = \frac{3E_0}{\lambda T_0 n}, \quad \tau = \frac{c^2R_0}{L_1m^2}t$$

The results of a numerical solution of the system (2.1), (2.2), (3.1), (4.2)-(4.4) for $B_1 = 0.3$ m^2, $B_2 = 0.5$ m^2, $B_3 = 8.5$, n = 20 and m = 2, 3, 4, 7, are given in Fig. 3. The points show the energy yield for different transformers.

With large values of the transformation coefficients, the current in the load is small; the plasma is strongly cooled by radiation and, at the start, its resistance rises. In this case, the explosion makes an appreciable energy contribution only at a rather high power, i.e., with rapid work of the generator. Since the energy losses of a dense plasma depend strongly on the temperature ($\sim T^4$), in the case under consideration the resistance of the plasma varies only slightly, i.e., by 2-2.5 times. The greatest amount of energy is developed in the load when it is matched with the generator through a determined transformer. With a rise in the value of m, the current in the load decreases and, along with it, the power of the heating. With a small value of m, there is an increase in the effective resistance of the load in the primary circuit, which leads to rapid relaxation of the magnetic flux. In the case under consideration, the optimal value of m = 4.

LITERATURE CITED

1. A. D. Sakharov, "Explosive-driven generators," Usp. Fiziol. Nauk, 88, No. 4 (1966).
2. A. D. Sakharov, R. Z. Lyudaev, E. N. Smirnov, Yu. I. Plyushchev, A. I. Pavlovskii, V. K. Chernyshev, E. A. Feoktistova, E. I. Zharinov, and A. Yu. Zysin, "Magnetic cumulation," Dokl. Akad. Nauk SSSR, 165, No. 1 (1965).
3. E. I. Bichenkov, "Explosive-driven generators," Dokl. Akad. Nauk SSSR, 174, No. 4 (1967).

4. E. I. Bichenkov, A. E. Voitenko, A. F. Demchuk, A. A. Deribas, B. I. Kulikov, Yu. E. Nestirikhin, and O. P. Sobolev, "Experiments with an explosive-driven magnetic generator under laboratory conditions," Dokl. Akad. Nauk SSSR, 183, No. 6 (1968).
5. R. Herlach and H. Knoepfel, "Megagauss fields generated in explosive-driven flux compression devices," Rev. Sci. Instrum., 36, No. 8 (1965).
6. F. Herlach and H. Knoepfel, "Explosive techniques for applications in experimental physics," Report to Lab. Gas Ionization 65/17 (1965).
7. H. Knoepfel, H. Kroegler, R. Luppi, and J. E. van Montfor, "The generation and switching of magnetic energies in the megajoule range by explosive systems," Lab. Gas Ionization, Euratom CNEN, Frascati (1968).
8. H. Knoepfel, Pulsed High Magnetic Fields, North Holland Publ. Co., Amsterdam–London (1970).
9. R. L. Conger, "Large electric power pulsed by explosive magnetic-field compression," J. Appl. Phys., 38, No. 5 (1967).