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BALLISTIC MAGNETOCUMULATIVE GENERATOR

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The reusable source of a pulsed magnetic field — a ballistic magnetocumulative generator (BMG) — is considered. Electrical engineering analysis of the efficiency of operation of the generator on an active-inductive load is performed. A method for calculating the two-dimensional distribution of the field in the busbars of the generator is developed. Experimental results are obtained for the operation of a BMG *model on some types of load.*

The existing types of pulsed magnetic field generators and those being developed are primarily capacitor storages with large working voltages or magnetocumulative generators, among which explosive expendable installations are in most common use [1]. So-called linear compression generators operating on the principle of "a reverse rail" gun have been mentioned repeatedly in the literature [2, 3], but insufficient experimental results are available for just one of such generators — a coaxial source of a pulsed current of up to 10 MA using a closing cylindrical armature [4]. The armature was previously accelerated in a ballistic setup and then, flying along a coaxial system of busbars, compressed the magnetic field. This installation can be called a ballistic magnetocumulative generator (BMG). The complex system of current supply, which, by virtue of the coaxiality of the main busbars, fails upon entry of the armature, and also the short working section of the generator [4] make the generator unsuitable for some problems, including the powering of high-speed electrodynamic accelerators for action on rocks, etc. A BMG with a rather long working section can be used as a source of energy for such high-speed installations. Of considerable interest is the possibility of applying a BMG to geophysical electroprobing using current pulses generated in a special coil or a loop [5]. A pulsed MHD-generator with a pulse duration of 1–100 sec developed in the USSR [6] has been used to advantage on such problems. A BMG produces short pulses (up to 10 msec), which can be treated as δ-pulses for geophysical probing processes. The wide frequency spectrum of such signals allows a considerable increase in the probing resolution [7].

Figure 1 shows a diagram of a linear BMG which is a continuation of the barrel of a ballistic installation (gun). The electrical circuit of the BMG is formed by one or several turns of busbars 4 located lengthwise on the inner surface of the generator channel 3. Preliminary powering of the BMG from an additional source 2 (a capacitor bank or a storage battery) gives rise to a magnetic flux in the generator volume. Entry of the armature 1 leads to short-circuit of the turns, the flux is compressed, and the magnetic-field energy of the generator and the load 5 increases due to the kinetic energy of the armature. When the BMG operates on an active–inductive load, the energy gain is determined by the two dimensionless parameters

$$\alpha = 2R_1/L'v, \qquad \beta = L_1/L'l,$$

where R_1 and L_1 are the load resistance and inductance, L' is the inductance per unit length of the generator, v is the speed of the armature, and l is the generator length.

Using the approximation of constant speed of the armature, it is possible to obtain analytical dependences of the gain on the parameters α and β. In the case of a working load in the form of ohmic resistance

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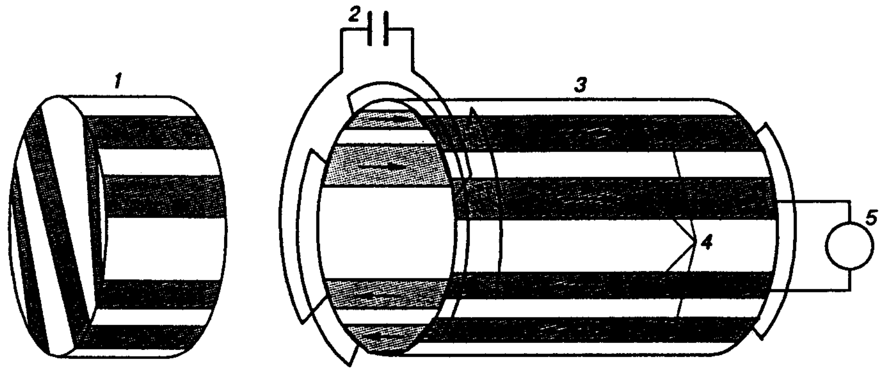

Fig. 1

R_1, the gain for the output Joule energy $Q = \int_0^t R_1 i^2 dt$ is defined as $k_e = Q/W_0$, where $W_0 = 0.5(L_1 + L'l)\, i_0^2$ is the initial magnetic energy of the circuit. As shown in [8], the dependence $k_e(\alpha, \beta)$ in this case has the form

$$k_e = \frac{\alpha}{1-\alpha}(\beta^{\alpha-1} - 1).$$

For an energy gain, it is necessary that the conditions $\alpha < 1$ and $\beta < 1$ be satisfied. The analysis in [8] shows that obtaining a considerable gain k_e for the operation of the BMG on an active loading ($R_1 > 10$ mΩ) is a complicated engineering problem.

The best coupling is attained when the BMG operates on an inductive load L_1 with low resistance ($R_1 < 1$ mΩ). In this case, the working energy is defined as $W_1 = 0.5 L_1 i^2$, and the gain is $k_e = W_1/W_0$. The dependence $k_e(\alpha, \beta)$ in the approximation $L_1 \ll L'l$ ($\beta \ll 1$) has the form $k_e = \beta^{\alpha-1}$. In the case of small Joule losses ($\alpha \approx 0$), this dependence becomes the known relation for ideal (lossless) circuits $k_e = 1/\beta = L'l/L_1$, i.e., the gain is defined as the ratio of the initial inductance of the circuit, which is equal to $L'l$ provided that $L_1 \ll L'l$, to the final inductance L_1.

The above relations give the integral performance of the BMG in an electrical engineering approximation. For an accurate calculation, it is necessary to determine the electromagnetic field in the entire volume of the generator. When the generator length is great compared to its cross section (caliber), one can ignore edge effects and consider this electrodynamic problem of determining the electromagnetic field in a two-dimensional approximation for the cross section of the generator channel. Figure 2 shows a diagram of one-turn BMG with busbars of rectangular cross section. In the calculation of the powering of the generator by a capacitor bank we solve, following [9], the two-dimensional diffusion equation

$$\gamma(\partial A/\partial t) = \Delta A + \gamma E^c, \tag{1}$$

where $\gamma = \sigma\mu$ (σ is the conductivity and μ is the absolute magnetic permeability), A is the vector potential, which has one component along the z axis of the channel in the two-dimensional case considered, and E^c is the z component of the "extraneous" field in the busbars, which in our case (the capacitor discharge) is the capacitor field.

At the initial time, the intensity E^c is maximal, but the current density j in the busbars is equal to zero because it also depends on the time derivative of the vector potential:

$$j = \sigma(-\partial A/\partial t + E^c). \tag{2}$$

Substituting the initial condition for the vector potential $A = 0$ into (1), we obtain $\partial A/\partial t = E^c$, which, according to (2), gives $j = 0$.

After completion of the stage of powering of the generator by the capacitor, for example, at the moment the current is maximal, there are certain distributions in the busbars of the current density j, the magnetic induction $\mathbf{B}(B_x, B_y)$, and the vector potential A. At this moment, the conducting armature —

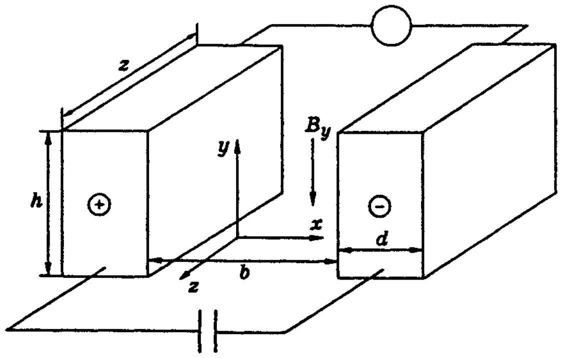

Fig. 2

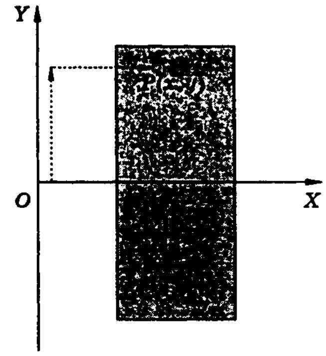

Fig. 3

sliding contact — begins to move along the busbars of the generator, leading to compression of the magnetic flux. In this stage, the distributions of the vector potential and the magnetic field in the busbars are also calculated using Eq. (1). However, the field E^c is no longer related to the electrostatic field of the capacitor but it is an induced field with an unknown distribution over the cross section of the busbars. In determining the field E^c, we take into account that the current density is obtained as in the case of the electrostatic field from formula (2). It is obvious that in any case (the capacitor field E^c or the induced field E^c) the following energy equality should be satisfied:

$$\int_{V(t)} \left(\frac{j^2}{\sigma} + \frac{1}{2\mu}\frac{\partial B^2}{\partial t}\right) dv = \int_{V(t)} jE^c dv. \tag{3}$$

Here $V(t)$ is the time-varying volume occupied by the field. This equality follows directly from the Maxwell equations in a quasistationary approximation (ignoring displacement currents), which is allowable in our case because the characteristic time of field variation is about 1 msec. On the other hand, for the generator with moving armature, the following balance equation should be satisfied:

$$\frac{z}{2\mu}\left(\int_S B^2 dx\, dy\right) + \frac{v\Delta t}{2\mu}\left(\int_S B^2 dx\, dy\right) = \frac{z-\Delta z}{2\mu}\left(\int_S B^2(t+\Delta t)\, dx\, dy\right) + \Delta t \cdot z \int_S \frac{j^2}{\sigma}\, dx\, dy. \tag{4}$$

Here z is the current (at time t) length of the generator section that has not yet operated, and v is the velocity of the armature; integration is performed over domain S, which is the entire plane XOY, and in the last integral, the domain S can be replaced by the cross-sectional area of the busbars. The left side of Eq. (4) contains energy terms that correspond to the magnetic-field energy at time t and the work done by the armature against the magnetic-pressure forces in time Δt. The right side contains the magnetic-field energy at time $t + \Delta t$ and the energy dissipated in time Δt. This equation can be written as

$$z\left[\int_S \left(\frac{j^2}{\sigma} + \frac{1}{2\mu}\frac{\partial B^2}{\partial t}\right) dx\, dy\right] = \frac{v}{\mu}\int_S B^2\, dx\, dy. \tag{5}$$

Comparison of (5) and (3) shows that the field E^c required for the calculation should satisfy the equality

$$\int_V jE^c dv = \frac{v}{\mu}\int_S B^2 dx\, dy.$$

For the two-dimensional case, the last equality is written as

$$z\int_S jE^c dx\, dy = \frac{v}{\mu}\int_S (B_x^2 + B_y^2)\, dx\, dy.$$

Here

$$j = \frac{1}{\mu}\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right).$$

The induced field can be represented as

$$E^c = \frac{v}{z}\,\Phi(x,y).$$

Then, for the function Φ, we have

$$\int\limits_S \left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right)\Phi(x,y)\,dx\,dy = \int\limits_S (B_x^2 + B_y^2)\,dx\,dy.$$

Integrating by parts and taking into account that the boundary of the domain of integration S is rather distant from the current-carrying busbars, where the magnetic-field induction decreases to zero, we obtain

$$\int\limits_S \left(B_x\frac{\partial \Phi}{\partial y} - B_y\frac{\partial \Phi}{\partial x}\right)dx\,dy = \int\limits_S (B_x^2 + B_y^2)\,dx\,dy.$$

The last equality is valid if the function Φ satisfies the following system of equations:

$$\frac{\partial \Phi}{\partial x} = -B_y, \qquad \frac{\partial \Phi}{\partial y} = B_x.$$

Taking into account that the equation $\mathrm{div}\mathbf{B} = 0$ leads to the potentiality of the vector with components $(-B_y,$ $B_x)$, we obtain the following integral representation for the function Φ:

$$\Phi[P(x,y)] = \int\limits_0^{P(x,y)} (-B_y dx + B_x dy).$$

The result does not depend on the integration path. In particular, choosing the integration path as shown in Fig. 3, we obtain

$$\Phi(x,y) = -\int\limits_0^x B_y(\zeta,y)\,d\zeta + \int\limits_0^y B_x(0,\eta)\,d\eta. \tag{6}$$

For busbars that are symmetric about the axis OX, we have $B_x(0,\eta) = 0$ and, finally,

$$E^c(x,y) = \frac{\varepsilon}{z} = -\frac{v}{z}\int\limits_0^x B_y(\zeta,y)\,d\zeta, \tag{7}$$

where ε is the induced e.m.f., which is equal to the rate of change of the magnetic flux through the region enclosed by the streamline that passes through the point with coordinates (x,y). The last result could be written immediately from the induction law, but the analysis performed led to the more general expression (6), which is also valid for asymmetric busbars.

In contrast to the above electrical engineering approximation, in which the armature velocity was constant, in the numerical model, the armature velocity is calculated in each time step using the equation of motion

$$M\frac{dv}{dt} = -\frac{1}{2}L' i^2,$$

where M is the mass of the armature, L' is the inductance per unit length of the busbars, and i is the generator current.

Equation (1) is solved by a difference method using an implicit scheme and decomposition along coordinates [10]. To make the algorithm universal outside of the busbars, we introduce a fictitious small conductivity equal to 10^{-5}–10^{-6} of the conductivity of the busbar material. We consider a generator with busbars of width $h = 0.1$ m and channel diameter $b = 0.1$ m (see Fig. 2). These values are in close to those of the experimental generator. For such dimensions, as calculations show, the effect of the busbar thickness on the current strength is insignificant. This is due to the relatively small Joule losses and the weak effect of the current-distribution characteristics over the cross section of such busbars on the magnetic energy. In the

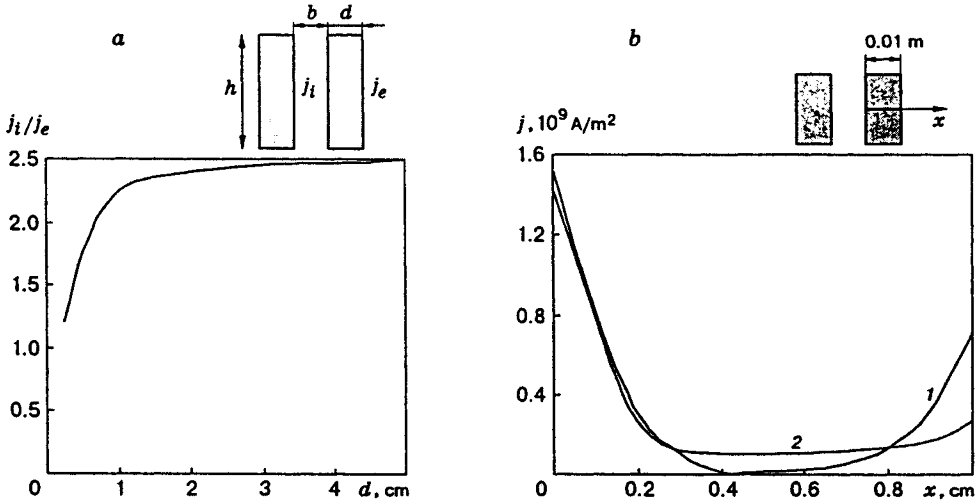

Fig. 4

calculations, we determine the effect of the busbar thickness and material on the current density at various points of the cross section of the busbar, in particular, on the busbar surface. The current distribution on each of the surfaces is homogeneous, except in the corner regions, where a considerable increase in the current density is observed.

A significant feature of the current flow in the system of busbars is the considerable current density on the outer surface of the busbars. Figure 4a shows the ratio of the current density for a pair of busbars powered by a capacitor versus the busbar thickness. The busbar length is $l = 2$ m and its width is $h = 0.1$ m, the spacing between the busbars is $b = 0.1$ m, and the capacitor capacitance is $C = 0.012$ F. To decrease the outer surface current density, one can use a compound busbar whose inner part is made of copper and whose outer part is made of a material with large resistivity. For such a two-layer busbar (curve 2 in Fig. 4b) with an outer steel layer, the current density on the outer surface is 2.5 times lower than that in the case of a homogeneous copper busbar (curve 1) of the same thickness (Fig. 4b).

At the stage of magnetic-flux compression, the current-density distribution changes. The current density on the inner surface of the busbars decreases severalfold, the current distribution becomes more uniform, and the characteristic skin-layer regions disappear. The calculation results indicate a decrease in the resistance of the BMG in the generation regime compared to estimates using the skin-layer model. However, in reality, there may be additional losses due to contact phenomena on the boundary between the armature and the busbars. Therefore, the main challenge in designing such a BMG is to ensure reliable contact of the armature with the current-carrying busbars.

To determine the performance of the setup, we performed experiments on a large-scale BMG model designed as a one-turn generator with channel inside diameter (caliber) 125 mm. This BMG has two diametrically opposite copper busbars separated by insulation inserts and placed in a body made of fiberglass winding. The armature of the one-turn generator is made of an aluminum alloy in the form of a barrel with a jacket having thin ring ribs, which collapse during motion along the generator channel.

The BMG model was tested in various regimes. The ballistics was tested by shooting the armature with the disconnected electrical circuit. The capacitor bank was discharged on the BMG without entry of the armature in order to test the powering system. Finally, we performed complex experiments in which the armature was shot into the generator volume at the moment the powering current was nearly maximal. The tests were performed for two types of load:

1) A low-impedance load in the form of shorting metal jumpers at the outlet of the generator busbars;

2) A geophysical loop model having much higher inductance and impedance than those in the first case.

Figure 5a shows the experimental dependence of the current for the case of shorting elements at the

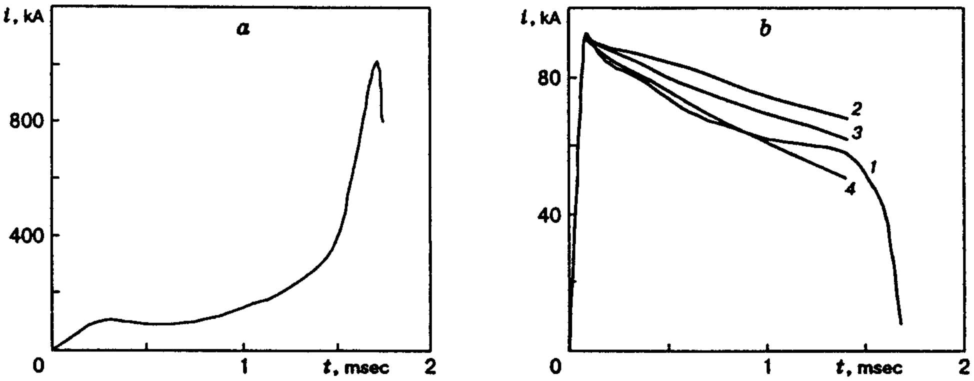

Fig. 5

exit from the BMG. The measurement results are as follows: initial powering current 77 kA, maximum current generated by the BMG 10^3 kA, and current gain $k_i = 13$.

The experimental dependence of the current i on time t can be approximated by the dependence used in calculations of explosive magnetic generators:

$$i(t) = i_0 \frac{L'l + L_1}{L_1 + L'(l - vt)} \exp\left[\frac{2R'}{L'}(\sqrt{t_0} - \sqrt{t_0 + t})\right].$$

Here L', R', L_1, l, and v have the previous meaning, and t_0 is the time from the beginning of powering to the moment the armature enters the BMG. It is assumed in this case that during the time of reswitching of the BMG circuit by the armature (100–120 μsec), energy cumulation does not occur, the generator inductance varies linearly, and the ratio R'/L' is constant throughout the operating of the generator. As a result, the following performance data for the BMG are obtained: $R'/L' = 6$ $\text{sec}^{-1/2}$, $R' = 3.84 \cdot 10^{-6}$ $\Omega^{-1} \cdot \text{m}^{-1}$, energy gain $k_e = 9$, and magnetic-flux conservation factor $k_\varphi = 0.75$.

Several tens of experiments were performed using the first type of load with considerable time intervals between series of starts (from several days to a year). The interval between starts in one series was rather short (10–100 min). In all experiments, the maximum current was close to 1 MA. This indicates the possibility of ensuring fairly stable performance of installations based on the BMG.

In experiments using a load in the form of a geophysical loop model, primary attention was given to the recording of current curves. From results of discharges of the capacitor bank on the joint load BMG+loop, we obtained the loop performance data ($L_1 = 0.273$ μH and $R_1 = 0.66$ mΩ). Figure 5b shows the generator current curve 1 for such a load. At the moment the armature entered the generator, the discharge current of the bank was nearly maximal and was equal to 92.5 kA. As was expected, the load current did not increase because of the insignificant inductance per unit length of the BMG model (0.64 μH/m). By the end of the generator operation, the current decreased by a factor of 1.5, but the effective pulse duration increased by a factor of five compared to the duration of the pulse from the capacitor bank on the same load. This shows the possibility of using the BMG as a pulse former in geophysical studies. Processing of the experimental current curve with the aim of determining the internal characteristics of the generator is of great interest. The generator inductance was determined with sufficient accuracy (0.96 μH) in measurements using an electrical bridge, and it agrees with the one determined from the curves of the capacitor discharge through the generator busbars on the loop.

The BMG resistance was approximated by a calculation model with a unilateral skin layer. The resistance per unit length was determined from the formula

$$R' = (1/h_{\text{eff}})\sqrt{2\pi\mu/\sigma t},$$

where h_{eff} is the effective width of the contact surface of the busbars, and the time t is reckoned from the moment the capacitor begins to discharge. In the case of a rigorously unilateral distribution of the current on the inner (from the side of the channel) surface of the busbar, the effective width coincides with the actual width of the busbar h. When the two-dimensional character of the field distribution is taken into account more rigorously, a skin layer also develops on the outer side of the busbar and its lateral surfaces. Hence, the effective width of the current layer should be greater than the actual width of the busbar.

Figure 5b shows calculated curves 2 and 3 for values of h_{eff} equal to $2h$ and h, respectively. It is evident that the calculated curves lie well above the experimental curve. Only for the value $h_{eff} = h/2$ does the calculated curve 4 practically completely coincide with the experimental curve. However, this coincidence takes place only to a certain moment (~1 msec), after which the calculated curve is below the experimental curve. The comparison performed leads to the following assumptions. In the initial period of motion of the armature in the BMG, the generator resistance includes not only the resistance of the skin layer but also an additional resistance, which can be explained by contact effects and the nonuniform current distribution on the surface of the busbars (corner effects). Some time after the entry of the armature into the generator (1 msec), these additional resistances considerably decrease, and this can be explained by "fitting" of the armature and other effects. In this case, the internal resistance of the busbars becomes much lower than the values calculated using the skin-layer model. The last circumstance was noted above in the discussion of the two-dimensional distribution of the field in the generator in the presence of the e.m.f. induced by the motion of the armature. As a result, the general resistance of the BMG considerably decreases (at $t > 1$ mc) and the experimental current curve becomes flatter.

The studies performed show the possibility of designing a new type of magnetocumulative generator based on contact interception of the current of a linear system of busbars using a moving current-carrying armature. Primary sources of energy used to accelerate armatures (gunpowder, gas and liquid combustible mixtures) have high energy density. This will make it possible to develop high powers on such installations at small mass and dimension characteristics. Coupling such sources to loads of various types requires additional investigation.

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