EXPLOSION-MAGNETIC GENERATOR WITH A PLASMA LOAD

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Explosion-magnetic generators (EMG) [1-6], which permit obtaining large pulsed currents and magnetic fields by using an explosion, are promising even as powerful electrical energy sources to supply different electrophysical apparatus. Papers devoted to the question of matching an EMG to an actively inductive load has recently appeared, however, the majority has the nature of preliminary estimates, and experimental investigations are still not numerous [4-7]. Effective energy transfer is realized only in an inductive load [6], and the energy transferred in experiments with a plasma and active load did not exceed the energy to power the EMG itself. Thus, in [4] where the load in the form of tantalum foil was connected directly into the EMG loop, 320 J was transferred to the foil for 2 kJ of energy supplied by a battery of condensers. In [5] an EMG with matching transformer was used to heat a gas-discharge plasma. The 10-kJ energy inserted in the discharge was 50% of the energy to power the EMG. In [7] 5-6 kJ was transmitted through a matching transformer and a fast-acting breaker to an ohmic load for a supplied energy of 8 kJ.

The ratio between the energy transferred to the load and the energy supplied is an essential criterion defining the efficiency and utility of the EMG.

An EMG similar to that described in [6] with insignificantly altered geometric dimensions and almost half the weight of explosive was used in this research. As control tests showed, these changes did not affect the magnitude of the energy being generated.

The EMG loop consisted of profiled copper busbars, cassettes filled with a 10-mm-thick plastic explosive, and a single-turn 0.16-m-diameter and 0.33-m-long solenoid which was the primary winding of the matching transformer. The initial EMG inductance was L_0 = 1.9 μH, the solenoid inductance was L_1 = 65 μH, and the weight of the explosive charge was 2.5 kg. The EMG power was identical in all the tests (W_0 = 60 ± 5 kJ).

The secondary winding of the matching transformer was a 7-turn single-layer coil wound from copper ribbon of 40 × 1.5 mm section on a dielectric carcass. The coupling coefficient between the solenoid and the EMG was k = 0.9–0.95. The load was connected to the secondary winding by 20 parallel 6-m-long FPK cables. The total inductance of the secondary loop, including the transformer winding L_2 = 3.2 μH, the cable L_C = 0.3 μH, and the load L_L = 0.1-0.5 μH, was approximately identical in all the tests and equalled $L = L_2 + L_C + L_L$ = 3.6-4.0 μH, and only the active load resistance changed. The discharge was initiated in normal density air by the electrical explosion of a differently sized foil. An erosion type discharge between coaxial electrodes separated by a dielectric was used as EMG load at a 10^{-2} mm Hg pressure. The change in load resistance was achieved by varying the geometric dimensions of the foil and the number of discharge gaps.

Aluminum foil 0.02 mm thick, of the areas 20 × 10; 40 × 15; 80 × 15 cm with an initial resistance of 3.0, 4.0, $8.0 \cdot 10^{-3}$ Ω, respectively, was used. The foil was pressed between flat electrodes with reverse leads in the form of a double symmetric frame form a 10-cm-wide copper strip. The loop symmetry achieved in this manner relative to the foil permitted equilibrating the ponderomotive repulsion forces acting on it by oppositely directed currents. The inductance of the frame with the foil was 0.33, 0.33 and 0.49 μH, respectively, for the above-mentioned foil sizes.

The currents and voltages in the EMG power loops and in the load were determined by using Rogovskii belts and ohmic dividers in the tests; the magnetic field intensity in the solenoid was measured by an inductive transducer; the spectral fluxes and the discharge radiation energy in the visible and infrared spectrum ranges were recorded by photodiodes.

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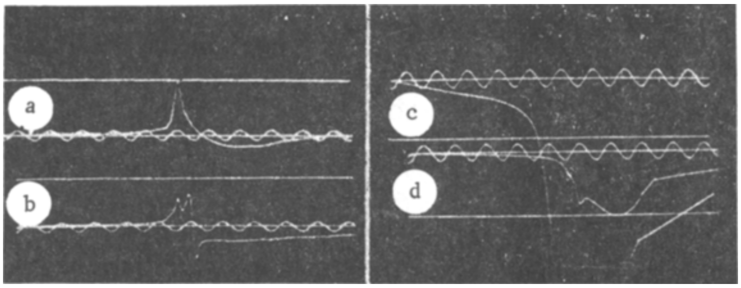

Fig. 1

The integrated output of the radiation energy was determined by using an IMO-2 calorimeter of two thermocouple and pyroelectric [8] transducers mounted at different distances from the discharge axis.

The dynamics of discharge development and the space–time plasma brightness temperature distribution in the discharge gap were investigated by a high-speed photorecording method (the results of the photorecording are not presented in this report).

Certain characteristic current and voltage oscillograms in the EMG load loop (Figs. 1a and b) and the magnetic field intensity in the solenoid for ~7-fold differences in the sensitivities of the oscilloscope inputs (Figs. 1c and d) are presented in Fig. 1 for an electrical discharge initiated by the explosion of a foil. The period of the scaling sinusoid is 100 μsec in all the oscillograms. Compression of the magnetic flux in the EMG loop starts at approximately 240 μsec and terminates at 540 μsec. The energy in the foil at the initial stage of EMG operation is expended in heating, melting, and evaporating it. The resistance of the discharge gap hence grows, and the current rise is accompanied by an increase in the voltage at the electrodes. The characteristic valley on the voltage oscillogram agrees, in time, with the time of signal appearance from the transducers recording the radiation, and corresponds to punchthrough of the discharge gap and ignition of the discharge in the air and the metal vapors. Development of the ionization processes results in a diminution of the discharge gap resistance, whereupon the voltage decreases for a certain time despite the rise in current. Abrupt maximums on the current and magnetic field intensity oscillograms correspond to the time t_m = 540 μsec of the maximum magnetic flux compression. A phase shift of the current pulses relative to the voltage pulse, which is characteristic for an active-inductive loop with a small active resistance, was observed in all the tests. The current maximum lags the voltage maximum by 5-15 μsec. For $t > t_m$ the magnetic energy stored in the inductances is liberated in the form of heat in the active resistors of the primary EMG and load loops. In contrast to tests with inductive load [6], the current pulse in these tests has a negative phase, whose amplitude and duration depend on the geometric dimensions of the foil.

The fundamental results of the tests are presented in the table, where the following notation is used: I_{10}, I_{20} are the currents in the primary EMG loop and the load at the initial instant of magnetic flux compression, I_{2m}, U_{2m}, H_m are the maximum values of the current and voltage in the load and of the magnetic field intensity in the solenoid, $I_{1m} = Nk_1I_{2m} + hk_2H_m$ is the maximum current in the solenoid (N = 7 is the number of turns in the transformer secondary winding, h = 0.33 m is the winding length, and k_1, k_2 are coefficients, close to one, characterizing the winding geometry [9]):

$$W_m = \frac{L_1 I_{1m}^2}{2} + \frac{L I_{2m}^2}{2} - M I_{1m} I_{2m}$$

is the maximum magnetic energy of the EMG (M is the coefficient of mutual induction); $E_m = \int_0^\infty I_2 U_2 dt$ is the energy liberated in the load up to the end of the current pulse; $J = \int_0^\infty I_2^2 dt$ is the current integral; $R_* = R_m/J$ is the "mean" load resistance, ε is the energy emitted by the discharge (in the air transparency domain for tests with foil and of quartz transparency for tests with erosion discharges); I_- and τ_- are the amplitude and duration of the negative phase of the current pulse in the load. Results of a test with a purely inductive load from [6] are also presented in the table for comparison.

TABLE 1

Load parameter	Foil				Erosion discharge			$R_L=0$ [6]
	20×10	20×10	40×15	80×15				
Test No.	2	3	4	5	6	7	8	16
I_{10}, kA	235	264	253	256	254	256	260	303
I_{20}, kA	23	22	23	19	0	0	0	31
H_m, kOe	52	62	65	66	64	75	54	60
U_m, kV	8,9	9,0	6,8	10,3	6,4	6,2	10,3	13,0
I_{1m}, MA	6,3	7,2	7,1	4,8	7,4	7,2	7,7	8,4
I_{2m}, kA	614	689	662	343	700	650	705	860
W_m, kJ	340	430	440	260	500	515	500	780
E_m, kJ	70	86	160	240	99	89	150	0
$J\cdot 10^{-6}$, $A^2\cdot$sec	12,3	16,4	14,7	4,40	13,6	10,6	18,5	22,2
$R_*\cdot 10^3$, Ω	5,7	5,1	11	54	7,3	8,4	8,2	0
ε, kJ	37	47	82	130	18	18	36	0
I_-, kA	65	131	130	95	184	181	68	—
τ_-, μsec	160	210	365	360	240	240	230	—

The tests showed a rise in the energy stored in the discharge (and emitted by the discharge) with the increase in geometric foil dimensions. Since the total load loop inductance varied insignificantly, as was mentioned above, it is natural to relate the change in the energy contribution in the discharge to the change in its resistance. Qualitatively it is clear that a small active, compared to the inductive, resistance in the load loop should not influece the magnitude of the currents and magnetic energy (tests 2-4), and the active energy $E_m = \int_0^\infty I_2^2 R dt$ should grow with the increase in resistance until it is substantially felt in the losses of the EMG magnetic flux. A further increase in the resistance results in a current reduction (test 5), therefore, the dependence of the energy being liberated in the load on the resistance should have a maximum. It is difficult to determine the location of the maximum according to the results of these tests since the discharge resistance itself depends on the stored energy and changes within the limits 10^{-3}-10^{-1} Ω during the pulse. Nevertheless, the ratios of the energy to the current integral presented in the table can be considered as "means" of the load resistance during comparison of the results of separate tests.

As is seen from the table, the energy in the tests with the foils grew from 70 to 240 kJ for a change from $5\text{-}50\cdot 10^{-3}$ Ω in the "mean" resistance. The currents I_{1m}, I_{2m} and the magnetic energy were reduced at the highest value of the resistance, but the active energy turned out to be greatest. Almost all the magnetic energy stored in the EMG prior to the time of maximum flux compressions was hence liberated in the load. This value of the resistence is apparently close to the optimal for given EMG and matching transformer parameters.

Time dependences of the energy liberated in the active load $E(t) = \int_0^t I_2 U_2 dt - \frac{L_L I_2^2}{2}$ are shown in Fig. 2 (the numbers show the number of the test). It is seen that until the time of maximum compression, the energy flux in all the tests is identical and equal to ~60 kJ. An energy increase is achieved as the resistance rises because of the negative phase of the current pulse.

The discharge radiation energy also grew with the increase in resistance, which was around 50% of the energy inserted in the plasma. The greatest value of the energy emitted (test 5) was 130 kJ.

Let us note that the fraction of emitted energy turns out to be greater compared to the known research on the electrical explosion of wires and foils. It is possible that under the conditions of these tests it is necessary to take account of the exothermal reaction of aluminum vapor oxidation in air in the total energy balance for comparatively slow energy liberation and considerable foil area.

Additional data on the influence of the load parameter on the efficiency of energy selection from the EMG were obtained in tests with the erosion discharge. There was no current in

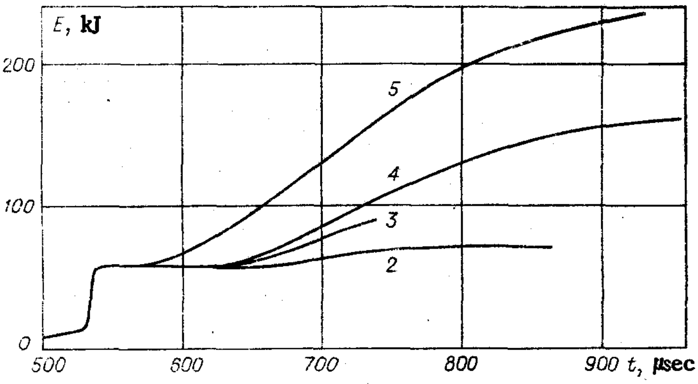

Fig. 2

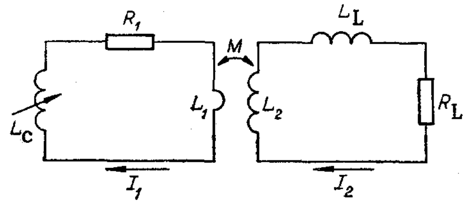

Fig. 3

the transformer secondary winding up to the origination of the discharge, and the EMG operated in the "no load" mode. The discharge occurred in tests 6 and 7 because of spontaneous breakdown of the discharge gap for ~ 20 kV voltages on the electrodes 30 μsec to the time of maximum-EMG flux compression. In test 8 two series-connected discharge gaps were initiated by an external igniting pulse at 70 μsec before, for an essentially lower voltage of ~2 kV. After the origination of the discharge, the nature of the oscillogram is analogous to that presented in Fig. 1. The maximum values of the currents and the magnetic energy were approximately identical in all three tests. The greatest active energy E_m = 150 kJ is obtained in a test with series-connected discharge gaps. The contribution of the negative phase of the current pulse to the energy is negligible. A rise in energy as the resistance grows can be expected by a further increase in the number of discharge gaps by analogy with the tests with foils.

The tests performed showed the possibility of transmitting a significant part of the EMG energy to a plasma load with a 10^{-2}-10^{-1} Ω active resistance through a matching transformer without an additional breaker of the type [7], whose application is related to large energy losses in the disconnecting.

Analysis of the operation in an EMG on the basis of the equivalent circuit displayed in Fig. 3 yields a quantitative explanation of the experimental results obtained. The change in inductance of the EMG is given by the functions

$$L_C = \begin{cases} (L_0 - L_1)\left(1 - \dfrac{t}{t_m}\right) & \text{for} \quad t \leqslant t_m, \\ 0 & \text{for} \quad t > t_m. \end{cases}$$

The remaining circuit parameters were considered independent of the time. The magnetic flux losses in the EMG loop were taken into account by the resistance R_1, whose magnitude was given in numerical computations on an electronic computer so that the maximum values of the currents I_{1m} and I_{2m} agreed with the experimental values for R_L = 0 (test 16, $R_1 = 1.4 \cdot 10^{-3}$ Ω). The values of R_L, L_2, and L_L varied.

For $R_1 \neq 0$ and $t > t_m$, the presence of a negative pulse phase, observed in the experiments, is characteristic for the computed time-dependence of the current in the load. Depending on the load resistance, the ratio I_-/I_{2m} has a maximum on the order of one for R_L = ~$[(L_2 + L_L)/L_1]R_1$. In the case of quite "small" or quite "large" R_L, the ratio I_-/I_{2m} is almost zero. Such a dependence on the loop parameters explains the fact, in particular, that the negative phase was not recorded in experiments published earlier.

The shape of the current pulse in the load is related to the redistribution of the energy stored in the form of magnetic field energy until the time of maximum flux compression. In the case $R_1 = 0$, it follows from an analytic solution of the electrotechnical loop equations that the main fraction of the energy stored in the transformer inductances remains in the primary loop. Only the energy stored in the load inductance is liberated in the second loop resistance for $t > t_m$, and there is no negative phase. In the more general case under consideration $R_1 \neq 0$, a part of the primary contour energy is indeed transmitted to the load.

Computations showed that the dependence of the energy liberated in the load on its resistance has a maximum which shifts toward greater values of R_L as the inductance of the secondary winding of the matching transformer increases. The greatest value of the energy (240 kJ) was obtained in test 5 in which the resistance is close to the optimal computed value $R_{opt} \approx 10^{-1}$ Ω. The possibility of a further increase in the active energy during diminution of the load inductance and by a proportional increase in L_2 and R_L for a given L_L follows from the computations.

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LITERATURE CITED

1. A. D. Sakharov, "Explosive-magnetic generators," Usp. Fiz. Nauk, No. 88 (1966).
2. H. Knopfel, Superstrong Pulsed Magnetic Fields [Russian translation], Mir, Moscow (1972).
3. E. I. Bichenkov, A. E. Voitenko, A. F. Demchuk, A. A. Deribas, B. I. Kulikov, Yu. E. Nesterikhin, and O. P. Sobolev, "Experiments with explosive-magnetic generators," Dokl. Akad. Nauk SSSR, 183 (1968).
4. Conger, Johnson, Long, and Parks, "Generation of powerful electrical pulses by the explosive compression of a magnetic field," Rev. Sci. Instrum., No. 11 (1967).
5. A. E. Voitenko, E. P. Matochkin, and B. A. Yablochenkov, "Use of an explosive-magnetic generator to supply a gas discharge," Prib. Tekh. Eksp., No. 3 (1973).
6. I. I. Divnov, Yu. A. Gus'kov, N. I. Zotov, O. P. Karpov, and B. D. Khristoforov, "Explosive-magnetic generator with an inductive load," Fiz. Goreniya Vzryva, No. 6 (1976).
7. E. I. Azarkevich, A. E. Voitenko, V. P. Isakov, and Yu. A. Kotov, "Explosive electric generator," Zh. Tekh. Fiz., 46 (1976).
8. Yu. N. Kiselev and V. Z. Krokhin, "Low-inertia pyroelectrical detectors to record radiation in the 40-1100-nm range," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1976).
9. P. L. Kalantarov and L. A. Tseitlin, Computation of Inductances. Handbook [in Russian], Énergiya, Leningrad (1970).

HEAT AND MASS TRANSFER OF AN AEROSOL DURING MIXING WITH THE FLUX OF A NONEQUILIBRIUM VIBRATIONALLY EXCITED MEDIUM

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The use of mixing of vibrationally excited nitrogen and carbon dioxide aerosol fluxes in order to improve the energetic characteristics and increase the homogeneity and volume of an active inversion medium was proposed in [1, 2]. It was assumed that the insertion of a solid phase CO_2 in a supersonic nitrogen stream in the initial stage might be performed by mechanical means without using the mechanisms of laminar and turbulent diffusion, whereupon mixing of the subsonic and supersonic fluxes is usually realized. Then because of the latent heat of sublimation of the solid phase, an additional reduction in the translational–rotational temperature of nitrogen and of the symmetric and deformational vibrational degrees of freedom of the CO_2 molecules can be achieved for a given degree of expansion of the main flow. The stagnation temperature and the nitrogen pressure in the forechamber can also evidently be raised by this method, and therefore, the population inversion is increased both because of the rise in the upper level vibrational temperature and because of the reduction in the lower level temperature. In order to realize these possibilities, the processes of aerosol interaction with a vibrationally excited gas must be analyzed thoroughly.

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