PERFORMANCE IN ENERGY TRANSFER FROM AN EXPLOSIVE MAGNETIC GENERATOR (EMG) VIA A MATCHING TRANSFORMER TO A LOAD

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Numerical calculations with the electrotechnical equations are used to define the optimum conditions for energy transfer from an EMG via a matching transformer to a resistive–inductive load. A comparison is made with experimental data for an EMG of planar type [1] for variations in the load inductance L_l and load resistance R_l in the ranges 0.4-6.3 μH and 0-2.6 Ω, respectively. In the experiments, the energy in the resistive load (up to 300 kJ) was 3-5 times the pumping energy of the EMG.

The performance of an EMG as an energy source is characterized by the ratio of the energy transmitted to the load to the energy W_0 used in the pumping to produce the initial magnetic flux. However, in many experiments with single-stage EMG of planar type, the energy transferred to a resistive load has not exceeded W_0 [2-4]. Therefore, calculations and experiments have been performed to define the conditions for optimum matching of an EMG to a resistive–inductive load.

The equations for the equivalent electrotechnical circuit [5, 6] of an EMG with an output transformer connected to the load take the form

$$\frac{d}{dt}(L_1 I_1) + R_1 I_1 - M\frac{dI_2}{dt} = 0, \quad L_2\frac{dI_2}{dt} + R_l I_2 - M\frac{dI_1}{dt} = 0, \tag{1}$$

where I_1 and I_2 are currents; $L_1(t)$, L_2, inductances; $R_1(t)$, R_l, resistance of the EMG circuit and the load, respectively; $L_2 = L_{2t} + L_l$; $M = k\sqrt{L_{1t}L_{2t}}$; L_{1t}, L_{2t}, inductances; M, mutual inductance; k, coupling coefficient for the transformer windings; $L_1(0) = L_0$; $L_1(T) = L_{1t}$; and T, magnetic-flux compression time.

As the initial conditions we took the conditions for the steady state for the currents in the transformer windings $L_1(0) = L_0$:

$$I_2(0) = MI_0/(L_2\sqrt{1 + (R_l\tau/2L_2)^2}),$$

where I_0 is the pumping current of the EMG from the capacitor bank, whose discharge period is τ, and in the experiments $\tau/2 \simeq T$. The calculations show that with the EMG parameters of [1] the maximum currents and energies were only slightly dependent on the initial condition for $I_2(t)$.

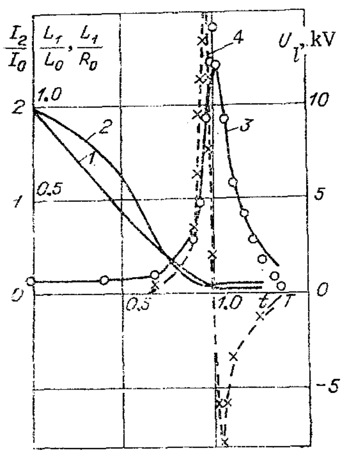

Fig. 1.

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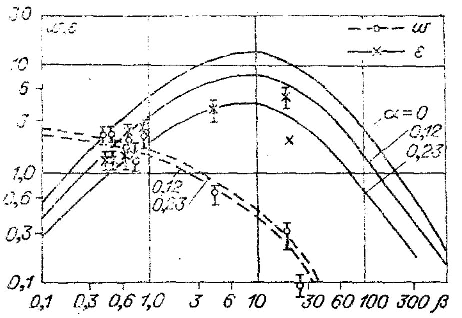

Fig. 2.

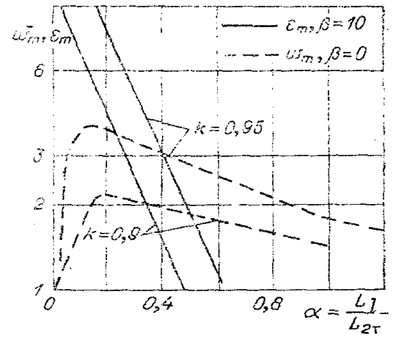

Fig. 3.

The function $L_1(t)$ was calculated on the basis of the known change with time in the geometrical parameters of the EMG circuit. The function $R_1(t)$ incorporating the loss of magnetic flux and energy in the EMG circuit was determined by solving (1) with the measured time dependences for the current $I_2(t)$ and voltage $U_l(t) = L_l dI_2/dt$ in the experiments of [1] with an inductive load ($R_l \simeq 0$). In several successive calculations, the values of $R_1(t)$ were modified in such a way that the difference between the values calculated with given $L_1(t)$ and $R_1(t)$ and the ones measured for $I_2(t)$ and $U_l(t)$ did not exceed the errors of measurement. In this way the experiments with $R_l \simeq 0$ yielded a function $R_1(t)$ that was then employed in calculations for any load parameters, i.e., it was assumed that the characteristics of the EMG were given and independent of the current. This has been shown to be so for an EMG of planar type [7] provided that the strength of the magnetic field in the EMG cavity did not exceed the limiting value $H_{li} \leqslant 260$ kA/cm. The condition $H < H_{li}$ was obeyed in all the calculations and in the experiments quoted here.

Figure 1 shows $L_1(t)/L_0$ and $R_1(t)/R_0$, where $L_0 = 1.85$ μH and $R_0 = 6.8$ mΩ are the initial values at $t = 0$ (curves 1 and 2), together with the characteristic $I_2(t)$ and $U_l(t)$ curves 3 and 4 for one of the runs (experiment 16 of [1]), the experimental values of $I_2(t)$ shown by circles and of $U_l(t)$ by crosses.

In the particular cases $R_1 = 0$ or $R_l = 0$, one can obtain the solution to (1) in the form of quadratures; the solutions for these cases have been examined [8, 9]. The equations in general form were solved numerically by using a program written by G. G. Vilenskaya. We introduce the dimensionless time $x = t/T$ and the new functions $i_1(x) = I_1/I_0$ and $i_2(x) = nI_2/I_0$, where $n = \sqrt{L_{2t}/L_{1t}}$ is the transformation coefficient, to get instead of (1) that

$$\frac{d}{dx}\left[\frac{L_1(x)}{L_0}i_1\right] + \frac{R_1(x)T}{L_0}i_1 - k\frac{L_{1\text{T}}}{L_0}\frac{di_2}{dx} = 0, \quad \frac{di_2}{dx} + \beta i_2 - \frac{k}{1+\alpha}\frac{di_1}{dx} = 0$$

with the initial conditions $i_1(0) = 1$, $i_2(0) = [k/(1 + \alpha)](1/\sqrt{1 + \beta^2})$, $\alpha = L_l/L_{2t}$; $\beta = R_l T/L_2$; in dimensionless variables, $w = (L_{1t}/L_0)\alpha i_{2m}^2$ and $\varepsilon = 2\beta(L_{1t}/L_0)\int_0^\infty i_2^2(x)dx$ are the maximum values of the magnetic energy in the load inductance and the energy deposited in the load resistance correspondingly as referred to the initial pumping energy of the EMG $W_0 = L_0 I_0^2/2$.

With given values L_1/L_0, R_1T/L_0 and L_{1t}/L_0 the results can be represented as dimensionless functions of the three parameters k, α, and β, which were varied over the ranges $k = 0.9 - 1.0$, $\alpha = 0 - 1$, $\beta = 10^{-2}$–10^3.

The calculations showed that the shape of the current pulse in the EMG does not vary qualitatively with the load parameters: $i_1(x)$ increases monotonically to a maximum at $x = 1$ and decreases for $x > 1$, while remaining positive. The shape of the load current pulse is substantially dependent on the load parameters. For small $\beta (R_l \to 0)$, the $i_2(x)$ dependence is analogous to $i_1(x)$, and $\varepsilon \sim R_l$, so the EMG works as a current generator. As β increases, the maximum in $i_2(x)$ shifts to $x < 1$, and after the maximum there is a negative phase in the current. For β large ($R_l \to \infty$), we have $i_2(x) \sim di_1/dx$, $\varepsilon \sim 1/R_l$ and the EMG works as a voltage generator. The maximum values of the currents i_{1m}, i_{2m} decrease as R_l and L_l increase.

Figure 2 shows the dependence of w and ε on β for $k = 0.92$ and $\alpha = 0$, 0.12, and 0.23. The energy w of the magnetic field in the load inductance is maximum for $\beta = R_l T/L_2 = 0$ and decreases monotonically as β increases, while the energy ε deposited in the resistance has

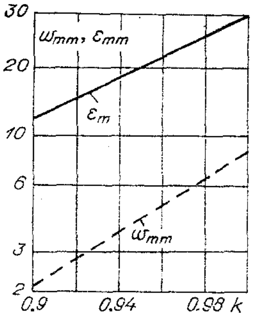

Fig. 4.

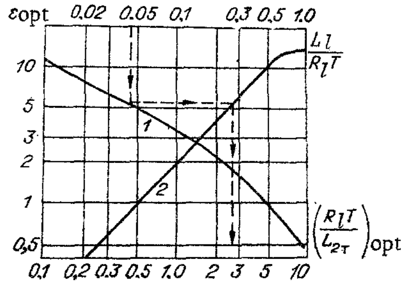

Fig. 5.

its maximum at $\beta = \beta_m \approx 10$. The position of the maximum varies little with α and k. For the given β, the value of ε decreases monotonically as α increases. The $w(\alpha)$ relation has a maximum whose position is dependent on β and k, with the maximum shifting to the right as β increases and to the left as k increases.

Figure 3 shows the maximum values of w_m and ε_m maximized with respect to β for $\beta = 0$ and $\beta = \beta_m$ correspondingly as functions of $\alpha = L_l/L_{2t}$ for two values of the coupling coefficient k = 0.90 and 0.95; for a given k, the maximum energy in the load resistance ε_{mm} occurs when $\alpha = 0$ and $\beta = \beta_m$; the maximum magnetic energy w_{mm} corresponds to $\beta = 0$ and $\alpha = \alpha_m$. Figure 4 shows the dependence of w_{mm} and ε_{mm} on the coupling coefficient, which characterizes the limiting performance of this EMG under ideal conditions for an inductive load ($R_l = 0$) and a resistive one ($L_l = 0$). Clearly, the matching transformer under optimum conditions transfers more energy to a resistive load than to an inductive one.

For given R_l and L_l, efficient energy transfer requires the choice of the optimum inductance for the secondary winding L_{2t}, which can be varied within wide limits via the number of turns n in the winding, since $L_{2t} \sim n^2$; to determine the optimum values $(L_{2t})_{opt}$ and ε_{opt} we show the results of the calculations in Fig. 5 for k = 0.92 as nomograms. From the given L_l/R , curve 1 of Fig. 5 is used to find ε_{opt}, and then curve 2 gives the corresponding values of $(R_l/L_{2t})_{opt}$ and $(L_{2t})_{opt}$. For the given EMG $\varepsilon_{opt} \leqslant 14$, and as R_l/L_l increases the efficiency in energy transfer to the resistive load rises, and the larger R_l, the larger the value of L_{2t} necessary to obtain the maximum energy. As the voltage in the load circuit increases simultaneously, the optimum value of L_{2t} may be restricted by the electrical strength of the insulation.

For small R_l/L_l, the value of ε_{opt} becomes less than one, but then there is an increase in the magnetic energy in the load inductance (Fig. 2), which can be transferred to the resistance by shorting the load circuit at the output from the transformer at the instant of maximum current.

Table 1 gives results from experiments performed with plasma and resistive–inductive loads at low and high resistances [1, 10-13]. In all the experiments, the following remain constant within the errors of measurement: the initial and final inductances of the EMG L_0 = 1.8 ± 0.2 μH and L_{1t} = 61 ± 3 nH, the coupling coefficient of the transformer windings k = 0.92 ± 0.02, and the magnetic-flux compression time T = 300 ± 5 μsec. The load parameters were varied within the ranges R_l = 0-2.6 Ohm and L_l = 0.4-6.3 μH. To provide matching to the load, the number of turns on the secondary winding was varied from 5 to 23. The EMG pumping energy was W_0 = 40-75 kJ.

In the experiments, measurements were made with an error of about 10% of the current and voltage in the EMG supply circuit and in the load, and also of the strength of the magnetic field within the transformer. The measurements were used with a special computer program [14] to calculate $I_1(t)$, W_0, and the energy in the inductance $W(t) = L_l I_2^2/2$ and that in the resistance $E(t) = \int_0^t U_l I_2 dt - W(t)$. When the plasma load was used, the calculation was based on a mean load resistance of $R_l = \int_0^\infty U_l I_2 dt / \int_0^\infty I_2^2 dt$.

The largest value E = 300 kJ was obtained in experiment 33 with R_l = 1.9 Ω and L_l = 3.9 μH, and up to the point of maximum current, 150 kJ had been deposited. The maximum voltage

TABLE 1

Expt. No.	R_l, mΩ	L_l, μH	L_{2T}, μH	W, kJ	E, kJ	α	β	w	ε
16	0	0,76	2,9	280	0	0,26	0	4,1	0
17	0	0,76	1,65	300	0	0,46	0	2,9	0
18	0	0,76	3,14	230	0	0,24	0	4,6	0
21	0	0,47	3,14	160	0	0,15	0	4,3	0
22	7,3	0,40	3,32	100	100	0,12	0,61	1,6	1,6
23	8,4	0,40	3,32	90	90	0,12	0,76	1,4	1,4
25	8,2	0,50	3,12	120	150	0,16	0,66	1,9	2,3
26	5,7	0,59	3,25	120	70	0,18	0,45	2,1	1,3
27	5,1	0,59	3,25	140	86	0,18	0,4	2,1	1,3
28	11	0,59	3,25	130	160	0,18	0,87	2,1	2,6
29	54	0,76	3,14	130	240	0,24	4,1	0,64	3,9
32	2600	6,3	28,7	5,5	96	0,22	23	0,09	1,7
33	1900	3,9	28	27	300	0,14	18	0,27	5,1

was 130 kV, peak power 15.6 GW, and ratio $\varepsilon = E/W_0 = 5.1$. Figure 2 shows the theoretical and experimental relationships for the energy transmitted to the load in terms of the load parameters. There is satisfactory agreement between the two within the possible errors. In most experiments, the energy obtained was close to the theoretical ε_{opt} for the given R_l/L_l. In certain experiments however, and in experiment 33 in particular, the conditions for optimum matching were not realized on account of voltage restrictions. Mainly for this reason, in the experiments we did not attain the maximum theoretical values $\varepsilon_{mm} = 10\text{–}14$.

These studies enable one to determine the conditions for optimum matching to any resistive–inductive load for an EMG of planar type with an output transformer [1]. To realize these matching conditions it is necessary to select the optimum inductance of the secondary winding of the transformer for each load.

LITERATURE CITED

1. I. I. Divnov, Yu. A. Gus'kov, et al., "An explosive magnetic generator with an inductive load," Fiz. Goreniya Vzryva, No. 6 (1976).
2. Conger, Johnson, et al., "Generation of high-power electrical pulses by explosive magnetic field compression," Prib. Nauchn. Issled., No. 11 (1967).
3. A. E. Voitenko, E. P. Matochkin, and B. A. Yablochenkov, "Use of an explosive magnetic generator for power in a gas discharge," Prib. Tekh. Eksp., No. 3 (1973).
4. E. I. Azarkevich, A. E. Voitenko, et al., "An explosive electrical generator," Zh. Tekh. Fiz., No. 46 (1976).
5. H. Knopfel, Ultrastrong Pulsed Magnetic Fields [Russian translation], Mir, Moscow (1972).
6. E. I. Bichenkov, A. E. Voitenko, et al., "A calculation scheme for connecting a planar explosive magnetic generator to a load," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1973).
7. E. I. Bichenkov and V. A. Lobanov, "The limiting currents in the compression of a magnetic flux between planar and coaxial conductors," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1975).
8. L. S. Gerasimov, "Matching an explosive magnetic generator to an inductive load," Zh. Tekh. Fiz., 44, No. 9 (1974).
9. A. I. Pavlovskii, R. Z. Lyudaev, and L. N. Pljashkevich, "Transformer energy output magnetic cumulation generators," in: Megagauss Physics and Technology, P. J. Turchi (ed.), Plenum Press, New York–London (1980).
10. I. I. Divnov, N. I. Zotov, et al., "Behavior of a cylindrical shell under dynamic loads set up by a strong magnetic field," dep. No. 2414, VINITI (1977).
11. I. I. Divnov, N. I. Zotov, et al., "An explosive magnetic generator with a plasma load," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1979).
12. V. V. Vladimirov, I. I. Divnov, et al., "A magnetic plasma compressor with an explosive magnetic energy generator," Zh. Tekh. Fiz., 50, No. 7 (1980).
13. B. D. Khristoforov, I. I. Divnov, and N. I. Zotov, "Experimental research of explosive-driven magnetic generator performance with resistive–inductive load," in: Megagauss Physics and Technology, P. J. Turchi (ed.), Plenum Press, New York–London (1980).
14. I. V. Savin, V. A. Sokolov, I. I. Divnov, and N. I. Zotov, "Digital oscillogram processing," in: Automation in Experimental Research [in Russian], Kuibyshev (1980).