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HIGHLY INDUCTIVE EXPLOSIVE-MAGNETIC GENERATORS WITH HIGH ENERGY GAIN FACTOR

V. A. Demidov, E. I. Zharinov,
S. A. Kazakov, and V. K. Chernyshev

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Spiral explosive-magnetic generators (EMG) are sources of powerful electromagnetic energy pulses [1-3]. One of the most important characteristics governing the practical realization of the spirals is the magnitude of the energy gain factor (K_E). The dimensions of the primary energy source depend directly on the amplifying capabilities of the EMG. Since the specific energy assured by explosive current generators is approximately three orders of magnitude higher than the specific energy of condenser apparatus ordinarily used to power an EMG, the volume of the initial energy source approaches the EMG volume only if the generator energy gain factor reaches $\sim 10^3$.

Two possibilities exist for raising the K_E of explosive-magnetic units. One is to produce cascade systems that are several EMG connected by using couplers (air transformers) and operating in succession [1-4]. In this case the energy gain factor of the whole system equals the product of the K_E of each EMG and can reach an arbitrarily high value. However, cascade generators are complex and costly units. Moreover, the presence of couplers considerably increases the size and weight of the system (e.g., the dimensions of an air transformer are commensurate with the dimensions of the EMG itself). Another possibility for obtaining high values of K_E is to increase the ratio $\lambda = L_0/L_f$ (here L_0 in the initial inductance of the EMG, and L_f is the load inductance) by raising L_0. Construction of the generator is not complicated in practice here. This paper is devoted to namely spirals with high initial inductance.

1. Electrical Field during Operation of Highly Inductive Spirals

As is known, electrical fields capable of resulting in the origination of breakdowns and energy reduction in the load are developed in the volume of generators because of the high rate of magnetic field growth with rapid compression of the magnetic flux. In the limit case, the maximal stress in spiral generators tends to the quantity $LdI/dt \simeq IdL/dt = (\Phi/L)dL/dt$, where L is the inductance, I is the current, and Φ is the magnetic flux. Especially high voltages are developed in highly inductive spirals since they are powered by a high magnetic flux (for a given flux in the load, the magnitude of the initial flux Φ_0 should be the higher, the greater the ratio L_0/L_f). Depending on the initial energy, the law of inductance variation, and the size of the system, voltages in an EMG can reach tens

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TABLE 1

Section No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Turn spacing, mm	1	1,12	1.25	1,5	1.75	2	2,5	3	3,5	4,5	6	8	11	16	24
No. of entries	1	1	1	1	1	1	2	2	2	3	3	4	6	8	12
Lead diameter, mm	0.62	0,72	0,95	1,05	1,25	1,5	0,95	1,05	1,25	1,05	1,5	1,5	1,5	1,5	1,5

and even hundreds of kilovolts. This explains the fact that highly inductive spirals with uninsulated turns operate extremely unstably (cf. [2]).

It is evident that for given spiral generator parameters the working voltage in its volume will have a minimum value if the quantity LdI/dt remains constant during the whole time of deformation. This means that the law of inductance variation for the spiral should be selected with flux loss taken into account.

The current I flowing in an EMG loop is determined by the differential equation

$$d(IL)/dt + R_{\mathrm{eff}} I = 0,$$

where R_{eff} is the effective resistance determining all the losses in the loop. The solution of this equation for the flux $\Phi = IL$ has the form

$$\Phi(t) = \Phi_0 \exp\left(-\int_0^t \frac{R_{\mathrm{eff}}}{L}\, dt\right).$$

Hence, the flux conservation coefficient is

$$\eta(t) = \exp\left(-\int_0^t \frac{R_{\mathrm{eff}}}{L}\, dt\right).$$

It follows from experiments that in highly inductive spirals operating without significant flux losses (breakdowns), the ratio $\alpha = R_{\mathrm{eff}}/L$ remains practically constant throughout the whole time of tapping the turns. Taking α = const, we can write

$$I(t) = \Phi_0 e^{-\alpha t}/L(t). \tag{1.1}$$

Differentiating (1.1) with respect to t, we obtain

$$\frac{dI}{dt} = \frac{\Phi_0 e^{-\alpha t}\left[\frac{dL}{dt} + \alpha L(t)\right]}{L^2(t)}.$$

Multiplying this expressions by L and taking $L dI/dt \equiv \mathscr{E} = \mathrm{const}$, we have

$$\frac{dL}{dt} + \left(\frac{\mathscr{E}}{\Phi_0} e^{\alpha t} + \alpha\right) L = 0. \tag{1.2}$$

The solution of (1.2) has the form

$$L(t) = L_0 \exp\left[(\mathscr{E}/\Phi_0 \alpha)(1 - e^{\alpha t}) - \alpha t\right], \tag{1.3}$$

which is the law for tapping the inductance of a spiral generator in which the maximum voltage between the cone of the central tube and the turns of the spiral is constant though-out the time of operation.

2. Modeling Spiral EMG

Questions of modeling occupy an important place in the investigation and development of explosive current generators. Clarificiation of the physical processes proceeding in generators is performed most expediently in models, rather than on large structures, since this reduces sharply the time for the investigation itself and the material expenditure.

Let the inductance, resistance, and time of operation of the model and the full-scale apparatus be denoted, respectively, by L_1, R_1, t_1 and L_1, R_2, t_2. Let us consider all the linear dimensions of the model diminished n times relative to the full-scale unit. Then equality $L_2 = nL_1$ is satisfied for any time $t_2 = nt_1$, and the flux conservation factors are written as

TABLE 2

Spiral diameter, cm	Test No.	L_0, μH	E_0, kJ	L_f, μH	I_f, kA	E_f, kJ	η	K_E
4	1	340	0,014	0,14	160	1,8	0,22	130
	2	340	0,025	0,14	210	3,0	0,21	120
	3	340	0,015	0,14	150	1,6	0,21	110
	4	340	0,014	0,14	150	1,6	0,22	120
8	5	650	0,035	0,27	260	9,0	0,33	260
	6	650	0,17	0,27	550	41	0,32	240
	7	650	0,21	0,27	620	52	0,32	250
16	8	1300	0,25	0,55	660	120	0,46	490
	9	1300	1,2	0,55	1450	570	0,46	480
	10	1300	1,8	0,55	1800	900	0,47	500

TABLE 3

Section No.	1	2	3	4	5	6	7	8	9	10	11	12
Sect. length, mm	120	60	60	120	60	60	120	120	120	120	120	120
Turn spacing, mm	6	7	8	10	12	14	18	24	32	48	72	96
No. of entries	1	1	1	2	2	2	3	4	6	8	12	16
Diameter of leads, mm	4,5	5	5	3,3	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5

$$\eta_1 = \exp\left(-\int_0^t \frac{R_1}{L_1}\,dt\right), \quad \eta_2 = \exp\left(-\int_0^{t_2} \frac{R_2}{L_2}\,dt\right).$$

If the equality $R_2 = R_1$ is satisfied at any time $t_2 = nt_1$, then

$$\int_0^t \frac{R_1}{L_1}\,dt = \int_0^{nt_1} \frac{R_2}{nL_1}\,dt, \quad \eta_1 = \eta_2.$$

However, such an n-fold increase in the generator dimensions will cause an n-fold diminution in the equivalent frequency $\omega = (2/I)dI/dt$, which will result in a $\sqrt{n}$-fold enlargement of the skin-layer depth and a diminution of $\sqrt{n}$ times in the active resistance of the loop. If the reason for the flux loss in the EMG is just the finite conductivity of the loop, then

$$R_2 = R_1/\sqrt{n}, \quad \eta_2 = \eta_1^{1/\sqrt{n}}. \tag{2.1}$$

This relationship is satisfied well for axially symmetric systems. Geometric flux cut-offs can play a noticeable part in spiral EMG.

Modeling spiral EMG was investigated on generators with spiral inner diameters of 4, 8, and 16 cm. The linear dimensions of these EMG are quite similar. The spiral of 8 cm diameter was selected as fundamental and the other two models were constructed by a twofold diminution or enlargement of all the dimensions. An 8-cm-diameter EMG consists of 15 sections 4 cm in length. The distribution of the inductance L(t) satisfies the relationship (1.3). The turns are wound by copper circular wire with high electrical strength. Outside they are covered by an epoxy compound. The spiral parameters are presented in Table 1. The central aluminum pipe has a 4-cm outer and 3-cm inner diameter, and the mass of the explosive material in the pipe is 0.7 kg.

Three or four tests were performed with each model. Powering of spirals at the initial energy was from condenser sources. The test results are presented in Table 2, where E_0, E_f are the initial and final energies of the EMG, and I_f is the current in the load.

A typical oscillogram of the derivative of the current recorded in test 10 is presented in Fig. 1 (4-μsec timing marks, ray 1 is 1 cm along the vertical and is $1.7\cdot10^{10}$ A/sec, ray 2 is $3.5\cdot10^{10}$ A/sec at 1 cm), and the time dependence of the current for test 10 is represented in Fig. 2.

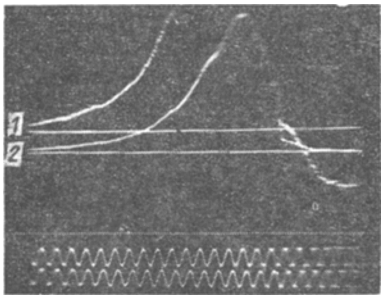

Fig. 1

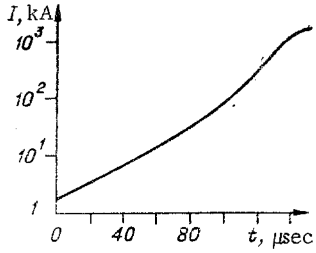

Fig. 2

TABLE 4

Test No.	L_0, μH	E_0, kJ	L_f, μH	$R_f \cdot 10^{-4}$, Ω	I_f, MA	E_M, MJ	E_T, MJ	E_f, MJ	K_E
1	305	14	0,34	10	4,1	2,9	0,2	3,1	220
2	305	16	0,34	3,2—24	4,5	3,4	0,6	4,0	250
3	305	24	0,34	3,0—10	5,4	4,9	0,5	5,4	225
4	285	28	0,34	3,2—26	4,8	3,9	0,7	4,6	165
5	285	16	0,34	10—19	3,7	2,3	0,4	2,7	170

It follows from Table 2 that the coefficients characterizing the efficiency of spiral activation (η, K_E) depend strongly on the system dimensions: The larger the size of the generator, the more efficiently it operates. This is seen especially graphically from the curves of $\eta(t)$ represented in Fig. 3, that are obtained by taking the average of values of η at each instant in all the tests for a given model (curves 1-3 are for the spiral diameters 4, 8, and 16 cm, respectively). Comparing values of η_1 and η_2 for any two models at the time $t_2 = nt_1$ shows that they satisfy the relationship (2.1) sufficiently well. This fact means that either the losses by cutting off are negligibly small in the spirals as compared with the ohmic losses, or the resistance due to them diminishes $\beta \sim \sqrt{n}$ times as all the linear dimensions in the system increase n times. The value $K_{2E} = K_{1E}^{\sqrt{n}}\lambda^{1-\sqrt{n}}$ can be found from the relationship (2.1) and the expression $K_E = \lambda\eta^2$. This regularity in the variation of the spiral energy gain factor as the size changes is well confirmed by experiments.

Graphs of $\mathscr{E}(t)$ are presented in Figs. 4-6 for tests 2, 7, and 10. The tests were performed under identical initial conditions, the values of E_0 for the spirals differed by approximately n^3 times. The values of $\mathscr{E}$ for the 4-, 8- and 16-cm spirals are as 1:2:4 for the tapping of the turns in the first sections, but these relationships were later spoiled. For the 8-cm-diameter EMG the $\mathscr{E}$ remained constant for almost the whole operating time (the drop in $\mathscr{E}$ in the last two sections is associated with the emergence of the pipe cone vertex from the volume of the spiral), which indicates good agreement between the real and design L(t) curves. For the 4- and 16-cm-diameter spirals $\mathscr{E}(t) \neq \text{const}$, consequently these generators, produced by a twofold change in the linear dimensions of the 8-cm-diameter EMG, are not optimal from the viewpoint of reducing the working voltages. A computation of L(t) with (2.1) taken into account must be performed for these spirals. Thus, if the value of $\mathscr{E}$ reaches 80 kV in test 10, then in the case of an optimal L(t) distribution, $\mathscr{E}$ will not exceed 70 kV, i.e., the working voltage will be reduced to ~15% under the same initial conditions.

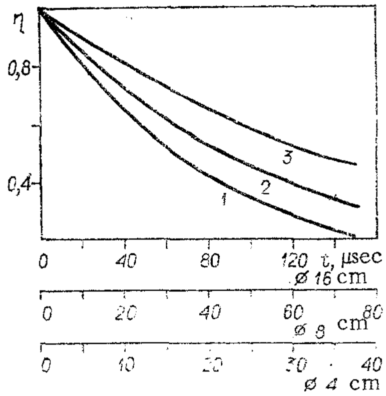

Fig. 3

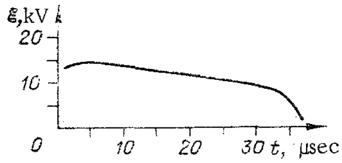

Fig. 4

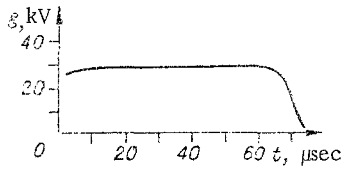

Fig. 5

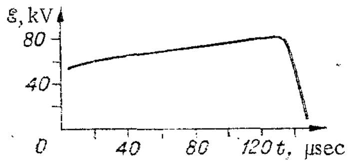

Fig. 6

3. Testing a 24-cm-Diameter Generator

The structural parameters of a 24-cm-diameter spiral coil are presented in Table 3.

The sections are wound with circular copper wire. The L(t) distribution was computed by means of (1.3). Copper central tubes with 110 mm outer diameter and 10 mm wall thickness, as well as aluminum tubes with 130 mm outer diameter and 20 mm wall thickness, were used in the generator. The mass of the explosive in the EMG is 13 kg. The generator load had the constant inductance 0.34 μH in all the tests; the initial resistance varied between $3 \cdot 10^{-4}$ and 10^{-3} Ω, and reached $(1-2.6) \cdot 10^{-3}$ Ω as the current grew.

The generator test results are presented in Table 4 for different initial conditions, where R_f is the load resistance, $E_M = I_f^2 L_f/2$ is the magnetic energy in the load, $E_T =$

$\int_0^t I^2(t) R_f(t)\,dt$ is the thermal energy in the load, $E_f = E_M + E_T$, $K_E = E_f/E_0$.

It is seen from Table 4 that the 34-cm-diameter spiral can assure finite energy, to ∿5.5 MJ, by having a stable value of the energy gain (220).

The dependence I(t) for test 3 is presented in Fig. 7. The maximum voltage at the load input is 45 kV in this test; the voltage in the spiral loop reaches 60 kV. It also follows from the test results that a diminution in the conduction of the central tube results in a certain reduction in the generator K_E.

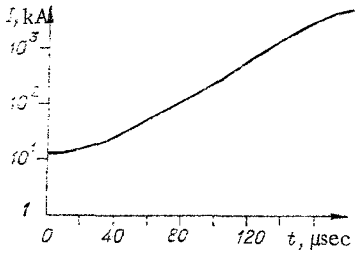

Fig. 7

4. Spiral EMG with $K_E \sim 10^3$

A series of five tests was performed with an 8-cm-diameter EMG and 72-cm-long spiral. The spiral coil with initial inductance of 490 μH has a 1.25-mm spacing of the first turns and 48-mm spacing of the final turns. For a power of 100-130 J initial energy in the load of 0.03-μH inductance, the generator stably assured a 2.8-3.2-MA current. The energy gain in the tests was 1000-1300.

As experiments showed, highly inductive spiral EMG with an optimal turn distribution along the axis and an insulated loop can magnify the initial energy 1000 or more times. The magnitude of the specific energy (the ratio between the final energy in the load and the initial EMG energy) is 30-60 J/cm³, while the energy conversion factor of the explosive into load energy is 4-8%. The magnetic field under the turns of the spiral reaches 1 MOe.

Taking the above into account, as well as the simplicity and economy of construction, it can be concluded that highly inductive spiral generators are convenient and reliable sources of electromagnetic energy pulses.

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