EFFECT OF AXIAL DISPLACEMENT OF LOOPS ON THE APPEARANCE OF BREAKDOWN IN A SPIRAL EXPLOSION-DRIVEN MAGNETIC GENERATOR

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Explosion-driven magnetic generators (EMG) are being increasingly used in physical experiments as sources of powerful pulses of electromagnetic energy. Among the existing EMG, one of the most promising and structurally simplest generators, which enables amplification of the initial energy by hundreds of times, are the high-inductance multisectional generators of the spiral type [1-4].

In this paper we study the effect of an axial displacement of the loops under the action of ponderomotive forces of the magnetic field on the appearance of electrical breakdown in a spiral EMG.

Let us examine one section of the spiral EMG with a constant loop-winding density, shown schematically in Fig. 1a. To determine the displacement of the i-th loop under the action of the radial component of the magnetic field, we construct the force function of the current [5], which in the Gaussian system of units has the form

$$F_i(z) = \frac{d}{dz}\left(\frac{1}{c}\,\Phi(z)\,I\right)_{z=z_i},$$

where

$$\Phi(z) = \frac{2\pi\mu}{c}\,Inr_0\int\limits_z^{\infty} h_{r_0}(z)\,dz$$

is the total magnetic flux through the cylindrical surface of a coil of radius r_0; I, current in the coil; $h_{r_0}(z, t) = cH(z, t)/nI$, dimensionless radial component of the field; l and n, length of the coil and the loop-winding density; and z_i, coordinate of the i-th loop. Based on the function F_i, the equation describing the axial motion of the i-th free loop with mass m_i has the form

$$m_i\frac{d^2z}{dt^2} = \frac{2\pi\mu r_0 n}{c^2}\,I^2 h_{r_0}(z_i,\,t),$$

and the loop displacement itself is determined by the expression

$$z_i = \frac{2\pi\mu r_0 n}{c^2 m_i}\int\limits_0^t dt\int\limits_0^t I^2 h_{r_0}(z_i,\,t)\,dt.$$

Since in a spiral EMG, because of the conical expansion of the central tube, the configuration of the magnetic field in the working volume of the generator is complicated and the numerical calculation of the function $h_{r_0}(z_i)$ is a laborious problem, the simplest way to find this function is to measure directly the radial component of the field H_{r_0} and the magnitude of the current I for a specific generator under laboratory conditions.

To this end, we selected the EMG (see Fig. 1a) consisting of a spiral coil 1, a central tube with the explosive change 2, and an inductive load 3. The geometrical parameters of the EMG were as follows: the length and radius of the coil loops was l = 24 cm and r_0 = 12.6 cm; the winding density of the loops was n = 0.5 cm^{-1}; the diameter of the copper conductor was d = 1.2 cm; the central tube consisted of copper and had an outer diameter of 8.5 cm and a wall thickness of 1 cm. The flare angle of the tube was α = 19°40'. The load was coaxial and had a length of 50 cm.

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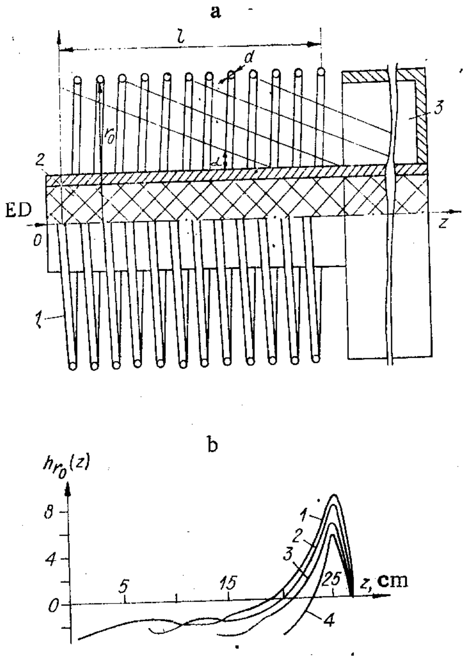


Fig. 1

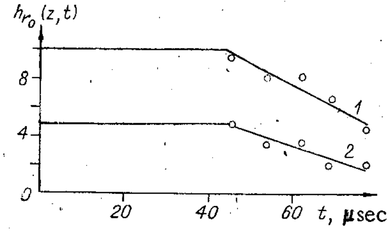


Fig. 2

During the laboratory measurements, in order to simulate the explosive expansion of the walls of the central tube, a metallic cone whose vertex angle was equal to the expansion angle of the central tube was inserted into the EMG.

The distribution of the magnetic field along the generatrix of the coil was measured with the help of differentiating probes, placed in the gaps between the loops, and the magnitude of the current in the coil was determined by an integrating Rogowski loop. The laboratory measurements of the function $h_{r_0}(z_i)$ for four fixed positions of the cone, i.e., in contact with the first, third, sixth, and ninth loops of the spiral [the loops in the coil are counted from the side where the electrodynamic apparatus (ED) is located], are shown in Fig. 1b (curves 1-4, respectively). The time dependences $h_{r_0}(z_i, t)$ were determined from the given family of curves. In particular, the functions $h_{r_0}(z_i, t)$ for the 11th and 12th loops are shown in Fig. 2 (curves 1 and 2, respectively). The displacement of the loops can be calculated from the known function $h_{r_0}(z_i, t)$ and the expected curve of the current in the generator.

To determine the effect of the axial displacement of the loops on the appearance of electrical breakdown, we performed a series of explosive experiments with the generator described above. In these experiments, the source of the initial energy was a capacitor bank with a capacitance of 1150 μF charged to a voltage of up to 30 kV (when the bank was discharged on the EMG, one quarter period of the discharge was equal to ≈240 μsec). The displacement of the loops and the possible appearance and development of electrical breakdown were observed with the help of an SFR-2M photochronograph, operating in the high-speed slow-motion camera mode. To increase the quality of the pictures, the coil was illuminated by two bursts of light. The discharge current of the capacitor bank was measured with a Rogowski coil, and the derivative of the current in the EMG was measured with differentiating probes placed in the volume of the coaxial load. The photochronograms were synchronized with the oscillograms according to the light flash from the spark discharge, the moment of whose appearance corresponded to the beginning of the discharge of the capacitor bank.

The first explosive experiment was performed with an EMG whose spiral loops were free and were not insulated. The experimental results (photochronogram and oscillograms of the derivatives of the current in the EMG) are shown in Fig. 3. Both rays in Fig. 3b are the derivatives of the current in the EMG; the time-marker spacing is 5 μsec. As is evident from the photochronograms, 272 μsec after the discharge of the capacitor bank starts, a local type electrical breakdown appears between the first and second loops of the coil. The region of breakdown expands with time, and transforms into a continuous volume discharge, encompassing virtually the entire inner space between the tube and the spiral. Characteristically, from the moment of the appearance of breakdown, irregularities in the form of random "jumps" appear in the oscillograms of the derivatives of the current, and instead of increasing smoothly the

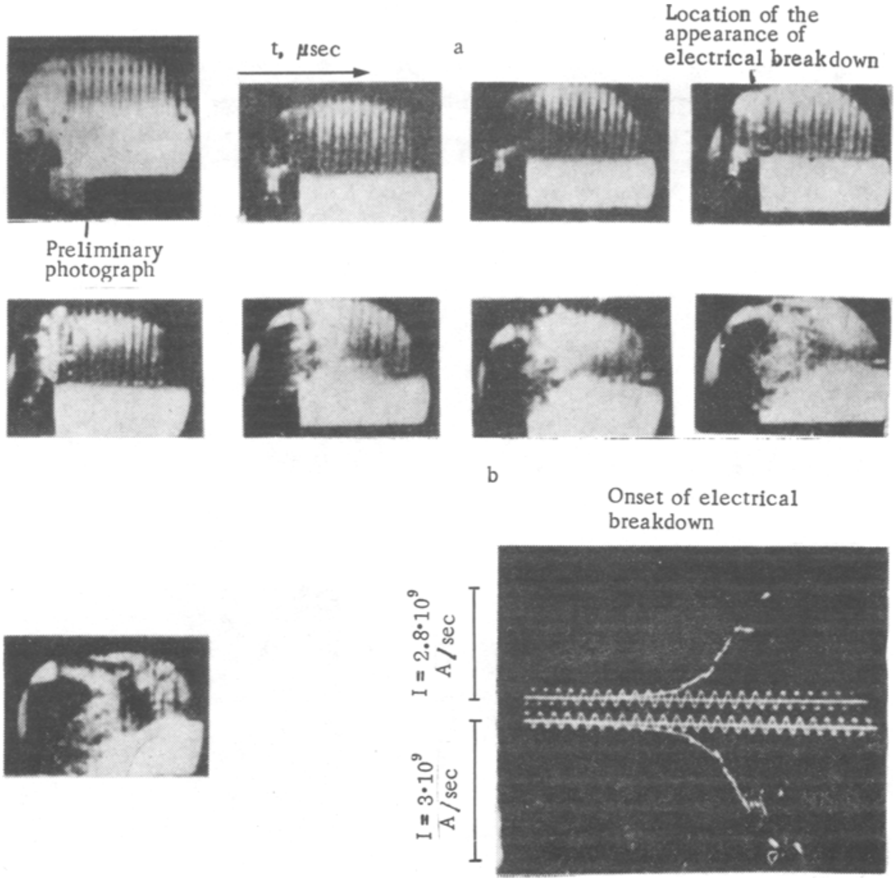


Fig. 3

curve $\dot{I}(t)$ acquires a sawtooth form. The jumplike change in the derivative of the current indicates the existence of cutoffs of the magnetic flux in the circuit, which, as is well known, decrease the magnitude of the final current. In the experiment described above, when an initial energy of 150 kJ was fed into the generator, the magnitude of the final current was equal to 800 kA.

In the second experiment, in order to decrease the displacement of the loops the energy fed into the generator was lowered to 65 kJ, and in order to increase the electrical strength of the EMG the loops of the spiral were insulated with a Lavsan film 0.1 mm thick. The experimental results are shown in Fig. 4. Both rays in Fig. 4b correspond to the derivatives of the current in the EMG; the time-marker spacing is 5 μsec. A final current of 1.2 mA was measured in the experiment. It should be noted that in spite of the measures adopted, electrical breakdown could not be completely avoided. As is evident from the photochronograms, breakdown occurred at the final stage of deformation of the circuit (298 μsec) between the 11th and 12th loops of the spiral, due to the destruction of the insulation on the loops as a result of their collision. Figure 5 shows the displacement of the 11th and 12th loops of the coil of the EMG (curves 1 and 2, respectively; the solid curve shows the calculation and the dots show the experimental values).

In the third experiment, the initial current in the EMG and the time at which energy was fed into the device were chosen so as to prevent the collision of the loops and thereby prevent the appearance of electrical breakdown in the working volume of the EMG. According to a preliminary calculation, the magnitude of the initial energy must not exceed 50 kJ and it must be fed into the device in a time of ∿60 μsec. Under these conditions, the axial displacement of the 12th loop will not exceed 2.5 mm at the end of the operation of the EMG. To determine more accurately the onset of breakdown in the coil, when it did appear the flashes were not used in this experiment. Figure 6 shows the experimental results. Both rays in Fig. 6b show the derivatives of the current in the EMG; the time-marker spacing is 5 μsec. Electrical breakdown was not observed in the spiral. The curves of the derivatives of the current increase smoothly without the characteristic "jumps." This generator produced a final current of ∿1.4 MA, which is higher than the current produced by previous generators.

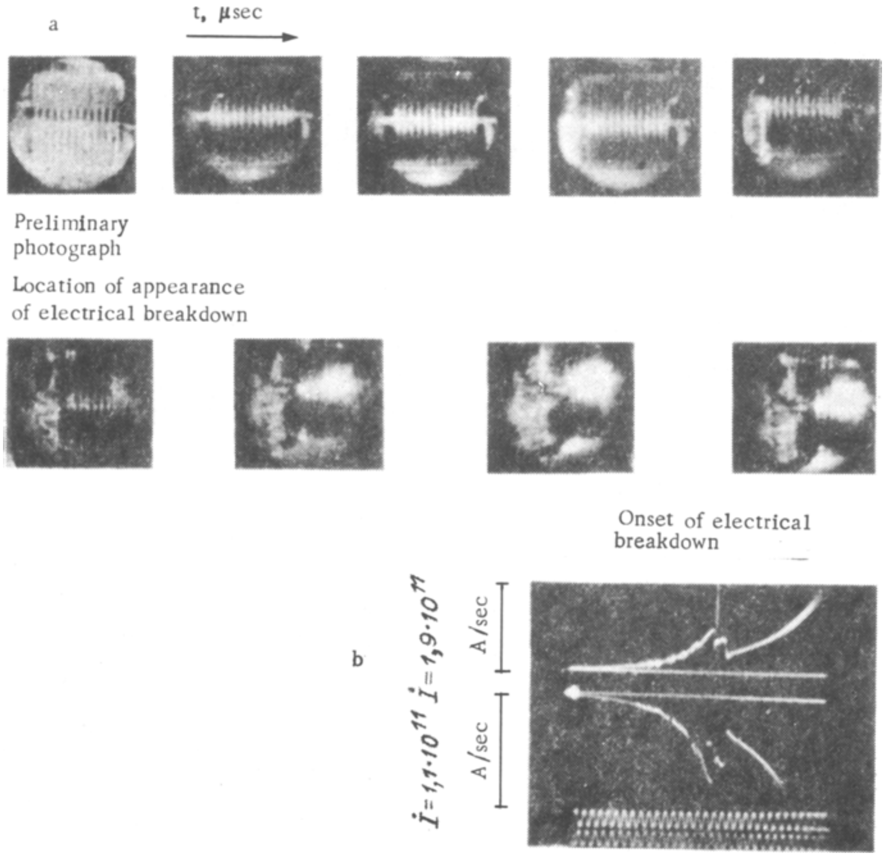

a
t, μsec
Preliminary photograph
Location of appearance of electrical breakdown
Onset of electrical breakdown
b
$\dot{I}=1,1\cdot10^{11}$ A/sec
$\dot{I}=1,9\cdot10^{11}$ A/sec

Fig. 4

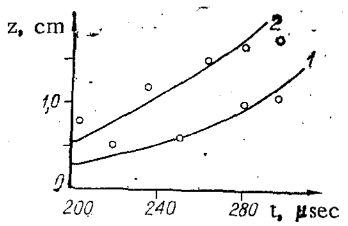
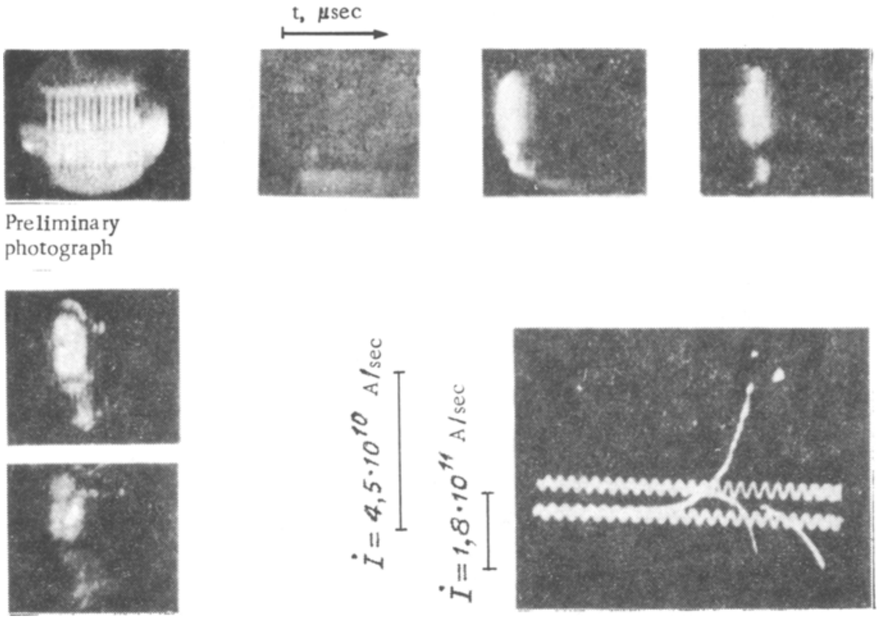

z, cm
1,0
0
200
240
280
t, μsec
1
2

Fig. 5


t, μsec
Preliminary photograph
$\dot{I}=4,5\cdot10^{10}$ A/sec
$\dot{I}=1,8\cdot10^{11}$ A/sec

In the course of the explosive experiments with EMG, it was established that the displacement of the loops leads to the appearance of electrical breakdown in the working volume of the EMG and lowers the magnitude of the final current. Electrical breakdown was eliminated by decreasing the axial displacement of the loops by lowering the magnitude of the initial current and decreasing its rise time and by insulating the loops. The adopted measures made it possible to increase the magnitude of the final current in the structure studied from 0.8 to 1.4 MA, i.e., by a factor of 1.7.

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INTERACTION BETWEEN A NONUNIFORMLY HEATED DIELECTRIC AND A MICROWAVE FIELD

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By using the abrupt growth of electrical conductivity with temperature, the authors of [1] accomplished the melting of a dielectric due to heat transfer to the solid phase from the melt absorbing hf power. The thermal regime of interphasal boundary motion during direct current heating of a melt and during induction heating was examined in [2]. In this paper, the structure of the heat wave is investigated, which is formed in the neighborhood of the melt during microwave heating. The thermal flux and field distribution is studied, and the limit values are determined for the parameter for which the thermal stability of the melt domain still holds.

1. If a melt section is produced in a waveguide with a dielectric filler* and power is fed from a microwave generator, then the melt will be heated by absorbing this power, will heat adjacent layers of the solid phase, and melt them. Therefore, the melt domain is propagated along the waveguide toward the generator. Because of secondary heat losses, this domain will be bounded. Motion of the melt boundary along the waveguide recalls propagation of a gaseous microwave discharge investigated in [3]. A problem of the light combustion wave in a solid dielectric, which is similar in formulation, was examined in [4]. However, the presence of a phase transition (accompanied by a jump in conductivity) results in a front structure and regularities of its propagation that differ from [3, 4], as will be shown.

Heating of the solid phase of the dielectric occurs because of the intrinsic absorption of microwave power as well as because of heat influx from the melt. The main part of the heat is liberated near the melt (at temperatures close to the melting point). Therefore, it can be considered that an "intrinsic" heat liberation source acts in a certain solid phase layer adjacent to the melt. The density of the power being liberated in the solid phase is small compared with the density of the power being liberated in the melt. However, it is generally impossible to neglect it since the ratio between the widths of the heat liberation domains in the solid and liquid phases is unknown in advance. It should be determined from

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*For sufficient dielectric permittivity of the substance simply a rod can be considered that will be a dielectric waveguide.

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