LIMITING CURRENTS IN THE COMPRESSION OF MAGNETIC FLUX BETWEEN FLAT AND COAXIAL CONDUCTORS

E. I. Bichenkov and V. A. Lobanov

UDC 538.4

Experiments are described on magnetic flux compression by flat and coaxial conductors. As the initial current I_0 is increased the final current I_1 obtained as a result of flux compression at first increases proportionally to I_0 and then reaches a maximum and remains constant for further increases in I_0. Analysis of the experiments shows that in coaxial structures when a small explosive charge accelerates the conductors the limiting current is determined by the maximum work which a conductor can perform in compressing the magnetic field. In experiments with flat busbars and large explosive charges the limiting currents appear to be determined by the flux losses in short-circuited voids formed in the linking of irregular surfaces of the busbars. This assumption is shown to be in qualitative agreement with experiment.

1. The first experiments with flat and coaxial magnetocumulative generators [1, 2] showed that in each of them only a quite definite final current I_1 could be obtained. The low mechanical strength of the devices described in [2] prevented discovery of the nature of the limiting current. Subsequently, experiments were performed with a very simple model of a flat magnetocumulative generator. A copper busbar 4 cm wide was bent into circuit 1 of length l_0 and a welded cassette 2 containing an explosive charge EC was placed at its center (Fig. 1). On the outside the busbars were loaded with steel covers or filled with concrete. This protected the busbars against displacement by magnetic forces and fixed the geometry of the cavity in which the magnetic flux compression occurred. A 10^{-2}-F capacitor bank with a working potential of 4 kV was discharged through the busbars. At the instant the current was maximum the explosive charge in the cassette was fired. The disintegrating walls of the cassette interlocked with the busbars compressing the magnetic flux. The point of contact of the busbars and the cassette was displaced along the busbars with a velocity equal to the detonation velocity D.

Some of the experiments were performed with coaxial conductors made of sections of copper and Duralumin tubes. The explosive charge was placed inside the smaller-diameter tube.

2. From an electrotechnical analysis of the operation of a magnetocumulative generator [3, 4] it can be expected that with an appreciable retardation path of a conductor in a sufficiently strong magnetic field and a small explosive charge the kinetic energy of the conductor will not suffice to compress the field. On the one hand, the power developed in the detonation of an explosive charge is qSD, where q is the specific energy of the explosive per unit volume and S is the cross section of the explosive charge. The fraction of this energy η which goes into kinetic energy of the conductor depends on the ratio of the mass of the explosive to that of the conductor being accelerated [5].

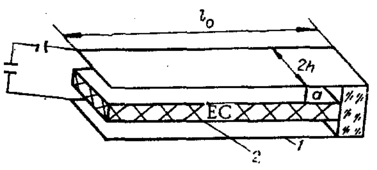

Fig. 1

On the other hand, in the deformation of a current-carrying circuit the pondermotive forces of the magnetic field develop a power $\frac{1}{2}I^2 \cdot (dL/dx)D$. The energy balance leads to the limiting current

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhanika i Tekhnicheskoi Fiziki, No. 5, pp. 116–120, September-October, 1975. Original article submitted January 10, 1975.

©1976 Plenum Publishing Corporation, 227 West 17th Street, New York, N.Y. 10011. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission of the publisher. A copy of this article is available from the publisher for $15.00.

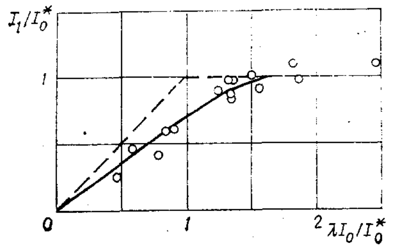

Fig. 2

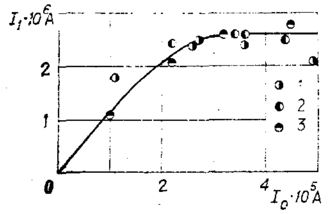

Fig. 3

$$I_0^* = \sqrt{\frac{2\eta qS}{dL/dx}}. \tag{2.1}$$

For a uniform magnetic field $dL/dx = 4\pi a/h$ and the field in the gap is $B = 4\pi I/h$, where h is the width of the busbar and a is the width of the gap. In addition, ηqs is the kinetic energy of a unit length of cassette wall, i.e., $\eta qS = \rho v_0^2 h\Delta/2$, where Δ is the thickness of the cassette wall. In this case it follows from (2.1) that the limiting magnetic field determined by the energy of the accelerated conductor is given by the expression

$$B_0^* = v_0 \sqrt{\pi\rho} \sqrt{4\Delta/a}. \tag{2.2}$$

In an ideal magnetocumulative generator the flux is conserved $LI = L_0 I_0$ and the final current is

$$I_1 = \lambda I_0,$$

where $\lambda = L_0/L$ is the compression factor. The energy condition (2.1) limits the final current to the value I_0^*. In the ideal case I_1 first increases proportionally to I_0 to I_0^* and then remains constant. The experimental results are conveniently represented in terms of the variables I_1/I_0^* and $\lambda I_0/I_0^*$. The broken line in Fig. 2 corresponds to an ideal generator and the solid curve shows the results of experiments with various coaxial generators. The experimental points for small $\lambda I_0/I_0^*$ lie below the curve for ideal generators, but within the limits of experimental error the energy-limited current I_0^* is reached as $\lambda I_0/I_0^*$ increases.

3. It follows from (2.1) that the limiting current should increase with a decrease of the linear inductance dL/dx. A series of experiments was performed with flat busbars in which the size of the cassette, the explosive charge, and the initial length of the busbars l_0 were fixed, but the distance a from the cassette wall to the busbar was varied. The results of this series of experiments are shown in Fig. 3, where points 1, 2, 3 correspond to a = 5, 10, 20 mm, respectively. The limiting current does not depend on the linear inductance. The results of these experiments are shown in Fig. 4 in terms of the variables I_1/I_0^* and $\lambda I_0/I_0^*$, where curves 1, 2, 3 correspond to a = 5, 10, 20 mm, respectively. In narrow gaps the limiting current I^* is from half to two-thirds as large as the energy-limited current I_0^*.

One can try to explain this result by flux losses in magnetic cumulation. The losses result from the diffusion of the field into the conductor and because of the capture of flux in voids formed in the joining of the rough surfaces of the busbars and the cassette walls. The diffusion losses in magnetic cumulation in narrow gaps was calculated in [6]. The calculation showed that although the flux losses are appreciable for magnetic Reynolds numbers of 10–50 the diffusion of the field into the conductor does not by itself lead to a limitation of the value of the current in the scheme of compression under consideration. In addition, the fraction of the flux retained in the generator voids depends strongly on the gap width a; i.e., the final current must depend strongly on a, which contradicts the experimental results cited (Fig. 3). Let us assume that the limiting current arises only because of contact flux losses. In this case the estimate of the limiting field obtained in [7] for a constant depth of the irregularities δ_0

$$\frac{B}{B_0} = \left(\frac{al_0 + S_0}{al + S_0}\right)^{1-\frac{2\delta_0}{a}},$$

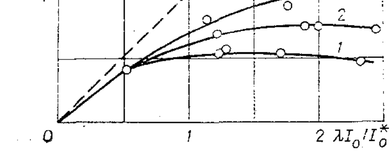

Fig. 4

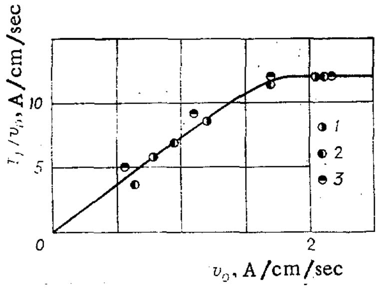

Fig. 5

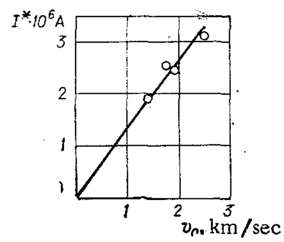

Fig. 6

shows that at the end of the compression ($l \to 0$) the limiting field depends on the size of the initial field B_0, the gap width a, the cross-sectional area of the residual inductance S_0, and as for (2.2) contradicts the experimental results.

Quite another result is obtained for contact flux losses by taking account of the fact that in strong magnetic fields the surfaces of conductors are deformed by the large magnetic forces. Let us assume that the rate of development of irregularities on the surface of a conductor is $v_1 = \alpha v_A$, where v_A is the Alfven velocity, α is some constant, and the time of development of the irregularities is equal to the time the cassette walls move before colliding with the busbars. Then the average depth of the irregularities is $\delta = \alpha a v_A / v$ and the equation of contact flux losses can be written in the form

$$\frac{dF}{dt} = -2\delta BD = -\frac{2\alpha a D}{v\sqrt{4\pi\rho}} B^2, \tag{3.1}$$

where v is the average velocity of the cassette walls, ρ is the density, B is the magnetic field, and F is the flux. After changing to the variable $l = l_0 - Dt$ and integrating, it follows from (3.1) that

$$B = \frac{\dfrac{v\sqrt{\pi\rho}}{\alpha}}{1 - \dfrac{l}{l_0}\left(1 - \dfrac{v\sqrt{\pi\rho}}{\alpha B_0}\right)}, \tag{3.2}$$

where B_0 is the initial field in the gap. Toward the end of the compression ($l \to 0$) the limiting field is obtained from (3.2):

$$B^* = v\frac{\sqrt{\pi\rho}}{\alpha}, \tag{3.3}$$

which does not depend on the initial value B_0 or the gap width a, but is determined solely by the velocity v. This means that for a constant width of the busbars contact losses determine the limiting current I^* whose magnitude is directly proportional to the average velocity v of the cassette walls and does not depend on I_0 and a. Equation (3.3) obtained for the limiting field is very similar to Eq. (2.2) for the energy-limited field. The difference is that α in (3.3) is assumed constant and the factor $\sqrt{4\Delta/a}$ depends on the distance a between the busbars and the cassette walls and the thickness of the cassette walls Δ. The experiments described in the present section show that under certain conditions the limiting current is smaller than the energy-limited current (Fig. 4) and does not depend on the distance a between the busbars and the cassette; i.e., it favors the assumption of current limitation by contact losses in accordance with the scheme presented for the development of irregularities.

4. To test the dependence of the limiting current I^* on the velocity and thickness of the cassette walls experiments were performed in which the geometry of the gap with the magnetic field was fixed and the thickness of the cassette walls and the weight of the explosive chosen were varied, leading to different velocities of the cassette walls and different values of their kinetic energies. The busbars of the generators were initially parallel to the walls of the cassette and at the end were bent at a small angle and approached the cassette, separated from it by a thin layer of insulating material. The linear inductance of such a generator was decreased toward the end and the limiting current I_0^* can be very large.

The experiments were performed for an initial velocity of the cassette walls v_0 = 1.4, 1.9, and 2.5 km/sec and wall thicknesses Δ = 2, 2, and 1 mm, respectively.

The results of these experiments are shown in Fig. 5 in terms of the variables I_1/v_0 and I_0/v_0, where curves 1, 2, 3 are for $v_0 = 1.4$, 1.9, 2.5 km/sec, respectively. In spite of the different thicknesses of the cassette walls the ratio I_1/v_0 remained the same, which contradicts the energy estimate (2.2).

Thus in the compression of a magnetic field by flat busbars there is a limiting current I^* whose magnitude does not depend on the way the conductor is slowed down in the magnetic field nor on its kinetic energy; i.e., the nature of this current is different from the nature of the energy-limited current I_0^* clearly observed in experiments with coaxial conductors, and probably can be related to contact flux losses in accordance with the scheme proposed.

The dependence of the limiting currents I^* on v_0 in the last two sets of experiments is shown in Fig. 6. On the basis of these experiments the coefficient α is 1.3, while other estimates of α give 0.7...0.9 [8]. Better agreement with [8] can be obtained for average velocities of the conductor less than v_0.

The experiments performed showed that in the compression of the magnetic field the limiting current is determined either by the energetic possibilities or by contact flux losses. Of the two possible values I_0^* and I^* the smaller is realized in experiments.

LITERATURE CITED

1. F. Herlach and H. Knoepfel, "Megagauss fields generated in explosive-driven flux compression devices," Rev. Sci. Instrum., 36, 1088 (1965).
2. E. I. Bichenkov, "Explosive generators," Dokl. Akad. Nauk SSSR, 174, 779 (1967).
3. E. Auvray, J. E. Besancon, and A. Ducauze, "Calculs et optimisation des generateurs de courant helicoidaux par explosif," Rev. Phys. Appl., 5, 301 (1970).
4. E. I. Bichenkov, A. E. Voitenko, V. A. Lobanov, and E. P. Matochkin, "Schematic diagram of design and wiring diagram for loading of plane explosive magnetic generators," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1973).
5. E. I. Bichenkov and V. A. Lobanov, "Acceleration of metal plates by an explosion," Fiz. Goreniya Vzryva, 10, No. 2 (1974).
6. E. I. Bichenkov and E. P. Matochkin, "Diffusion of flux in magnetic cumulation in narrow gaps," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1974).
7. H. Knoepfel, Pulsed High Magnetic Fields, North-Holland, Amsterdam (1970).
8. E. I. Bichenkov and V. A. Lobanov, "Flux losses in the compression of a magnetic field by flat busbars," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1975).