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Electrical Nonlinearity of Magnetodynamic Nature in Metals at High Levels of Energy Dissipation

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In cryoconductors of Corbino geometry made from uncompensated metals the phenomenon of nonlinear coupling between electrical field and current density is observed at rather low density of radial current. Nonlinearity is caused by a magnetic field of azimuthal drift of carriers due to the Lorentz force in an external magnetic field of the solenoid. In this report the results of investigation of the nonlinear phenomena in aluminum disks at different levels of dissipation of electrical energy are presented. The level of dissipation substantially redefines the thermal condition of system. Research was carried out by a method of registration of current-voltage characteristics in a preset current mode. Samples had different surface-volume ratios at a variation of their geometrical forms. In particular the samples in the form of a disk with a constant height along radius and also with a hyperbolic axial section are used. Measurements have been carried out in magnetic fields up to 8 T at loading current density up to 800 A/cm^2. The opportunity of existence of the asymptotic steady temperature-electric domain structure is discussed. Domains result in stabilization of current-voltage characteristic through the mechanism of non-local heat removal.

Key words: electric nonlinearity, electric field, magnetic field, Corbino geometry, uncompensated metal, magnetodynamic properties, cryoconductor, Hall field

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1 Introduction

Nonlinear electrical properties of metals are known to take place under excitation of metal surface with electromagnetic field in radio-frequency range of spectrum [1]-[4]. Usually electromagnetic waves are substantially reflected by a surface of metal and penetrates inwards on small depth. For example in optical range of frequencies, i.e. when frequency value is about frequency of plasmas fluctuations, the sole characteristic length named after skin depth takes place. Non-linearity for this case means the dependence of skin depth, reflection coefficient and surface impedance on intensity of radiation. The reason of these effects is the influence of magnetic field component of wave on dynamic of particles. In pure materials at low temperatures the free length of particle is large to be the factor of influence of magnetic field of wave on dynamics of charged particles and current lines [5]-[7]. Under stationary electro-magnetic field the nonlinear electrical properties are observed both in metal films and in volume samples. These properties take place due to the influence of an external steady magnetic field on particle movement under the conditions of absence of transverse electrical field called Hall field [8]-[10]. Sample is to be of Corbino geometry for an absence of Hall field was realized. Here some aspects of electrical non-linearity of magnetodynamic nature at steady current flow are discussed. The talk is about the conditions when the level of energy dissipation is enough to disturb temperature field of sample and respectively the additional mechanisms of systems heat organization are turn in.

2 Experimental procedure

To stimulate high levels of energy dissipation the special steps have been done to enlarge the resistance of sample and heat generation. It is known that the samples of Corbino geometry made of non-compensated metals have a very large resistance as a result of lateral drift of particles. In comparison with traditional Hall geometry the resistance in an external magnetic field is much higher of zero-field that. It is proportional to the factor of magnetic efficiency $\omega\tau$ to the power close to two (here ω is a Larmor frequency, τ is a relaxation time). To stimulate the influence of heat fields on nonlinear electric structure an additional factor as a form of Corbino geometry sample have been used. During study there were measured samples with different forms of axial sections. Among measured samples there were these having an axial section as rectangle. Corbino samples were taken as short and long cylinders. Besides there were used the samples having an axial section as a trapezium where a local height increases with radius. Also the samples having a hyperbola generatrix were used during measurement. All these profiles of axial sections have been selected to model the dispersed heat sources of different kinds including homogeneous and non-homogeneous that. Also these different sorts of axial sections were chosen to study the influence of geometrical factor on self magnetic field generation. So for an axial section as a rectangle the radial current density is a reversal function of radial coordinate. The situation is similar to solenoid that has increasing diameter of wire in layers at moving from inner to outer diameter. Respectively the level of local energy dissipation decreases along radius from inner to outer that. For sample having an trapezoidal axial section the level of energy dissipation decreases along radial coordinate at moving from inner to outer diameter as reversal function of radial coordinate to the second power. For the sample having a hyperbolic generatrix the cross section for radial current was not a function of radial coordinate. The picture resembles usual wire solenoid having a hyperbolic generatrix. For this case a heat source was homogeneous. Nonlinear electric properties of material in steady field are observable via an electric field potential being measured on sample surface with help of potential probes. This approach is called a method of voltage-current characteristics. To control the surface sample temperature during the experiment the temperature sensors were mounted on the surface. Contact areas were small and these probes did not influence on sample heat regime. The latter is determined both the velocity of heat generation via dissipation of electric field energy and the intensity of heat moving away via evaporation of liquid helium. The regime of current generator used usually for low temperature measurements in metal was ensured with current supply having output resistance of units of Ohms and output current value up to 1800 ampere.

3 Results and discussion

The voltage-current characteristics for Corbino samples having different profiles of axial section are similar in some aspects. At that time there are definite peculiarities being quite unlike quantitatively and qualitatively. Similar properties are the result of magneto-dynamical nonlinearity. For relatively simple case of electric non-linearity under the conditions excluding the excessive heat generation and temperature redistribution on volume the voltage measured initially on a sample surface displays only a dependence of resistance on current under an external magnetic field B_0. It is important that the voltage-current characteristics are invariant at the inversion of field direction B_0. Characteristics change in sign and absolute value at the inversion of current I. So there are two principle geometries of current flow named as collinear geometry (the own drift field B_s coincides with a field of solenoid B_0) and anti-collinear geometry (B_s is opposite to B_0). The voltage along radius at collinear geometry of a current flow is more than at anti-collinear one.

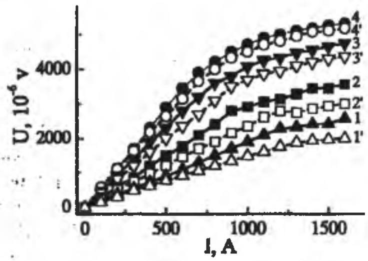

FIG. 1. Voltage along disk radius as a function of a current under external magnetic field B_0, T: 3.5 (1, 1'); 4.9 (2, 2'); 7.1 (3, 3'); 8.4 (4, 4'); 1, 2, 3, 4 - collinear geometry of current flow, 1', 2', 3', 4' - anti-collinear geometry. Disk thickness is 1 mm.

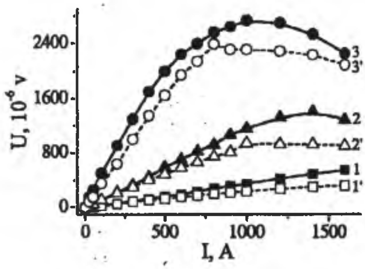

FIG. 2. Voltage along disk radius as a function of a current under external magnetic field B_0, T: 2 (1, 1'); 4 (2, 2'); 6 (3, 3'); 1, 2, 3, 4 - collinear geometry of current flow, 1', 2', 3', 4' - anticollinear geometry. Disk thickness is 2 mm.

On the other hand the experiment has shown that the macroscopic voltage-current characteristics of various Corbino samples differ qualitatively and there are several types of their behavior. For a thin disk with constant thickness equal 1 mm and outer diameter of 35 mm the characteristic is monotonous in all current diapason (Figure 1).

It was mentioned early that the electrical nonlinearity is caused by an additional resistivity stimulated by a magnetic field of charge drift [11], [12]. The primary linear dependence of voltage on current condition observable at small values of charge density changes and trends to saturation at large levels of charge density. The main peculiarity of discussed material is that at large current density the relative scale of magnetodynamic non-linearity decreases. In other words the distance between curves for collinear and anti-collinear geometry is the same in wide range of current for current values being higher of 500 A [13], [14]. This decrease is especially manifested under high levels of external magnetic field. As it was mentioned early in usual nonlinear regime the distance between lines belonging to collinear and anti-collinear geometries slightly increases for low current densities [15]. Also for low magnetic field the transition from pure non-linear regime to saturating one have fracture type.

Current diapason corresponding to linear area decreases with a magnetic field increase. It is essential that for such a sample the magnetodynamic contribution to the non-linearity of the characteristic remains dominating above heating processes in all current diapason.

For thicker disk (thickness is 2 or 4 mm and outer diameter is 35 mm) the behavior of voltage is linear. The linearity takes place at small values of current. However for all current diapason a voltage U as a function of a current I is non-linear function of I and passes through its maximum in strong magnetic fields (Figure 2).

At anti-collinear geometry the extreme is extended, and in some current diapason the voltage trends to stabilization. It is interesting that for anti-collinear geometry the transition from pure linear regime to non-monotonic behavior have more abrupt fracture type. After this jump there is an area in which the characteristic behavior is almost constant with subsequent decreasing of voltage. The value of current responsible for transition to non-linear regime decreases with growth of an external magnetic field.

At last for the disks having hyperbolic axial sections an abrupt jump down of voltage for both collinear and anti-collinear geometry of current flow with subsequent ideal stabilization takes place [10]. The characteristic consists of two parts

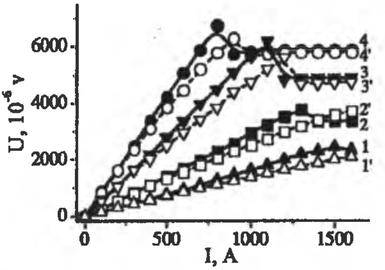

FIG. 3. Voltage along radius of a disk having hyperbolic section as a function of a current under external magnetic field B_0, T: 3.5 (1, 1'); 4.9 (2, 2'); 7.1 (3, 3'); 8.4 (4, 4'); 1, 2, 3, 4 - collinear geometry of current flow, 1', 2', 3', 4' - anti-collinear geometry.

separated with voltage jump down. The value of voltage at jump decreases with decrease of an external magnetic field (Figure 3). Linearity of the characteristic is peculiar both for collinear and anti-collinear geometry of a current flow. The initial part of characteristics is purely a result of a self magnetic field influence on resistivity.

Respectively the linearity in secondary part of characteristics could be explained as a consequence of heat field redistribution. The voltage jump in a disk reminds the current jump in a ballast lamp [16]. So the redistribution of a heat field over disk is connected with appearance of temperature structure being similar to temperature structure of ballast lamp. Behavior close to voltage stabilization (Figure 2) is also to have some elements of heat distribution being qualitatively similar to heat field of ballast lamp heat. The voltage being a function of current can be represented as $U \propto AI + \alpha I^2$, here linear part reflects usual Ohm law and non-linear addition is a correction associated with the influence of self magnetic field on charge movement. This expression corresponds to initial part of characteristics and such an approximation correlates with an approximation for self magnetic field inclusion to voltage along sample radius [12]. Secondary part of characteristics corresponds to expression for voltage of the next form $U \propto RI$; $R \propto C/I$: $C = Const$.

For voltage current characteristics of ballast lamp at stabilization regime being proved under large voltage supplied the next relation is actual $I \propto U/I$; $R \propto U/C$; $C = Const$. Here a definite type of reversal connection being ensured with heat field redistribution takes place. For Corbino sample a similar connection between heat field organization and electrical properties is to be take place.

4 Concluding remarks

For uncompensated metals an electrical nonlinearity being stimulated with magneto-dynamic nature of movement of charged particles is strongly sensitive to heat state of material. Pure cold non-linearity as a result of self-action of systems via lateral Hall current begins to decrease when temperature enlarges. Both local and global self-heating trends to suppress the own magnetic field and its influence on specific resistance. Respectively the difference between voltage current characteristics for collinear and anti-collinear geometry of current flow disappears. Further enlarge of radial current leads to suppressing of efficiency of an external magnetic field and the voltage current characteristics begin at last to display negative differential resistance. The degree of influence of energy dissipation on electrical properties is determined in considerable measure with a ratio between sample surface and its volume including sample form which defines the spatial distribution of heat source and intensity of heat removal.

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