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V. V. SYCHEV, V. B. ZENKEVICH, V. V. ANDRIANOV

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Experimental data known from the literature make it possible to conclude that the inductance of a superconducting solenoid situated in the magnetic field produced by the current flowing through it increases monotonically with increasing current (and, correspondingly, with increasing magnetic field). At large values of the current, the inductance of the superconducting solenoid comes close to the value characteristic of the same solenoid with a paramagnetic winding, while nevertheless remaining appreciably below the latter. At current values corresponding to a field of 1–2 kOe, the inductance of the solenoid becomes equal to the calculated inductance of a solenoid with an ideally diamagnetic winding and does not change upon further decrease of the current.

A typical curve of the dependence of inductance on current is given in [(1)]. In the case considered, the inductance of a solenoid made of 7752 turns of Nb–25% Zr wire varied in the interval 0.2–0.95 H when the current was changed from 1 to 12 A (the maximum value of the magnetic-field intensity at the center of the solenoid was somewhat below 30 kOe). On the other hand, in the literature [(2)] results are presented for measuring the inductance of a superconducting solenoid placed in an external uniform magnetic field. Only a small measuring current (30 mA) with a frequency of 1 kHz flowed through the solenoid winding. As the field was increased to 60 kOe, the inductance of the solenoid increased by only 4%, and at higher fields it rapidly increased to a value equal to the inductance of a solenoid with a paramagnetic winding. Previously it seemed that such a difference in the character of the change in inductance was connected with a difference in the physical situation and was due to the fact that in one case the field is produced by the current flowing through the winding of the solenoid itself, whereas in the other case such a current is absent. Nevertheless, the remark made in work [(2)], that the sharp difference between the values of the inductance of a superconducting solenoid in a field up to 60 kOe and the inductance of a solenoid with a paramagnetic winding is connected with the diamagnetism of the volume occupied by the winding, appeared doubtful. According to the data of the same work, in fields of the order of 60 kOe the superconducting winding has a relative magnetic permeability practically equal to unity.

In carrying out experiments connected with the operation of superconducting solenoids in direct- and alternating-current circuits, and also in studying transient processes in magnetic systems on superconductors, we established that a number of effects cannot be explained on the basis of existing ideas about the inductance of a superconducting solenoid and the character of the dependence of the inductance on the current flowing through the superconducting winding. Moreover, it turned out that the very concept of the inductance of a superconducting solenoid requires substantial clarification.

The circumstances indicated, as well as the fact that the value of the inductance is the most important characteristic of a superconducting magnetic sys-

···led us to the necessity of carrying out special experiments to measure the inductance.

The experimental solenoid consisted of 11,062 turns of Nb–33% Zr wire 0.2 mm in diameter. The wire was insulated with viniflex varnish and had no metallic coatings. The inner diameter of the winding was 16 mm, the outer diameter 51.5 mm, and the winding height 37.5 mm. The filling factor of the winding with superconducting material was 0.525. Since, in order to ensure the "purity" of the experiment, wire without a stabilizing coating was investigated, the critical current of the solenoid was relatively low and amounted to 11.5 A; accordingly, the maximum field at the center of the solenoid was 32 kOe.

Experiments of two types were carried out on this solenoid:

a) A special power-supply unit for the superconducting solenoid made it possible to superpose, on the direct current flowing through its winding, a small alternating component. The magnitude of the measuring alternating current was 1 mA. The frequency of the alternating current was chosen to be 80 Hz. At this frequency the active resistance of the superconducting solenoid to alternating current can be completely neglected. The inductance of the solenoid can be calculated from the measured value of the resistance of the alternating component of the current. It is clear that, for a small amplitude of the alternating current, the measurement results give the value of the so-called dynamic inductance L^{dyn}, defined by the equality

$$L^{\text{dyn}} = d\psi/dJ,$$

where ψ is the flux linkage of the solenoid.

b) In experiments of the second type, the solenoid, at a specified value of the direct current J flowing through it, was disconnected from the power-supply system by means of a vacuum contactor and became closed through a discharge resistance of the order of 1 ohm. The process of current decay lasted several seconds. During this time, oscillograms were taken of the voltage values at the ends of the solenoid and of the current flowing through the discharge resistance. These two quantities are interrelated; therefore their separate measurement, with the measurement system we adopted, made it possible to verify that the transient process in the vacuum disconnecting contactor did not affect the experimental results. Apparently, with a high degree of accuracy it may be assumed that, in the transient process under consideration, there is no energy dissipation in the solenoid winding; in any case, the release in the winding, in the form of heat, of an amount of energy at all comparable with the amount of energy released in the external circuit would have led to an avalanche-like transition of the solenoid to the normal state, which would have been recorded in the experiment. This allows one to assume that the voltage measured at the ends of the solenoid is equal to the emf of self-induction. Thus

$$E = -d\psi/d\tau,$$

where E is the voltage at the ends of the solenoid, and τ is time.

Integration of the dependences $E = E(\tau)$ from the corresponding oscillograms makes it possible to obtain the flux linkage ψ for a given value of the initial current in the solenoid J_0 and to calculate the value of the so-called static inductance

$$L^{\mathrm{st}} = \psi/J_0.$$

By choosing different values of the initial current, one can obtain the dependence $L^{\mathrm{st}} = f(J)$. On the other hand, when the solenoid is discharged from a given initial current J_0, for $J < J_0$ one can calculate the values of the static inductance by integrating the curve $E = E(\tau)$ with a variable limit of integration. The dependence on current of the values obtained in this way···

We shall denote the set of values of the inductance by $L^{\mathrm{st}}_{J_0} = \varphi(J)$, where J_0 enters as a parameter. In doing so, we do not prescribe in advance that the functions $f(J)$ and $\varphi(J)$ coincide.

The experimental results are presented in Fig. 1. The inductance measured in the first group of experiments (line 1) is practically independent of the current and is 1.00 H. The values of the inductance L^{st} obtained in the second group of experiments increase with increasing current, and the character of the dependence on current is the same as in work (1). The discrepancy between these two results cannot be explained, from a formal mathematical standpoint, as the usual difference between dynamic and static inductance. Indeed, the data for L^{st} make it possible to calculate L^{dyn} from the formula

$$L^{\mathrm{dyn}} = L^{\mathrm{st}} + J\, dL^{\mathrm{st}}/dJ.$$

Fig. 1. Results of measuring the inductance of a superconducting solenoid

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Since in the second group of experiments a positive value of dL^{st}/dJ was obtained, the curve of dynamic inductances calculated on the basis of these results will pass still higher than curve 2 in Fig. 1. If it is assumed that, in the process of discharging the solenoid, some fraction of the stored energy is dissipated in the superconducting winding itself, then the discrepancy between the inductance values observed in the two groups of experiments will also be still greater.

Thus, the fact that the inductance measured from the resistance to alternating current practically does not change with the change in magnetic field and is equal to the inductance of a solenoid with an ideally diamagnetic winding is not connected with the presence or absence of a direct current flowing through the solenoid winding. The phenomenon under consideration also cannot be connected with the diamagnetism of the winding, since the results of the solenoid-discharge experiments show a regular increase in inductance corresponding to an increase in the magnetic permeability of the superconducting material.

It was assumed that, for a small change of current in the superconducting winding, only the external flux linkage changes. The energy of the magnetic field inside the winding remains practically unchanged owing to the interaction of the magnetic flux with the superconducting material. In that case, the resistance to alternating current of small amplitude is connected only with the so-called external inductance of the solenoid, L_e, and the results of the measurements in the first group of experiments must give the value of the external inductance (since the experiments yield a constant quantity of 1.00 H, one need not distinguish between static and dynamic inductance).

For small magnetic fields (an ideally diamagnetic winding) this conclusion is trivial. If it should turn out that the external inductance of a paramagnetic solenoid is also close to 1 H, then the assumption under consideration would be proved. With the aid of an electronic digital computer, a calculation was performed of the energy of the magnetic field contained inside a paramagnetic winding of the corresponding dimensions.* On the basis of the results of this calculation and the measured value of the total inductance of the solenoid at nitrogen temperature (1.80 H), the value of the external

* The calculation program was written by V. G. Manuilov.

of the inductance of a paramagnetic solenoid, 0.971 H, which agrees well with the experimental results. (The possible change in the external inductance by 2-3% is of the same order of magnitude as the experimentally obtained change in the solenoid constant $n = H_0/J$, where H_0 is the field strength at the center. In the present work effects that are an order of magnitude larger are considered.)

The invariance of the internal flux linkage at the initial stage of the solenoid-discharge process, and the subsequent presence of a difference between the current value of the internal flux linkage and the corresponding equilibrium value, lead to a regular divergence between the functions L^{st} and $L^{\text{st}}_{J_0}$ considered above. (The functions $L^{\text{st}}_{J_0}$ for several values of J_0 are shown in Fig. 1 by dashed lines.) Moreover, the analysis shows that, in the course of a single discharge, at the initial stage the energy of the magnetic field in the volume of the winding may even increase, owing to the fact that, as the external flux linkage decreases, motion of the magnetic field through the winding material occurs, with the "capture" by pinning centers of an additionally determined number of fluxoids.

Experiments on solenoid discharge were carried out after a preliminary smooth increase of the current to the initial value J_0. In the case where the value J_0 is reached by slowly lowering the current, the resulting values of L^{st} lie above curve 2 and are reproduced relatively poorly. Such a result is entirely natural in light of the considerations discussed.

Results analogous to those considered above were also obtained in experiments with solenoids made of wire of alloy 65BT.

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Note: Figure translations are in progress. See original paper for figures.