2762/2-80

23/VI-80

объединенный
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исследований
дубна

E8-80-165

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INFLUENCE OF THE LOSSES ON THE HIGH CURRENT DENSITY SUPERCONDUCTING MAGNET WINDING STABILITY DURING THE ENERGY REMOVAL PROCESS

Submitted to "Cryogenics".

1980

At a rapid decay of the magnetic field one may consider the high current density (HCD) superconducting magnet (SM) winding heating up process as an adiabatic one. Such rapid decay of the magnetic field takes place during the energy removal from SM. The losses which influence the SM transient parameters were qualitatively pointed out by Glasov et al.[1].

The purpose of this paper is to obtain the experimental and calculational evidence for the quench possibility of the HCD SM winding due to losses generated during the energy removal from SM. This way the losses can affect the energy removal efficiency, since at definite protection device parameters it is dependent on the determined character of normal resistance going up in the SM winding. In some cases it is advisable to turn normal a large part of SM winding to protect the small part of it from overheating, as the dissipated energy tends to be concerned in the normal part of the magnet winding. The character of the quench process was examined. Experiments were carried out on the laboratory type solenoid SM[2] at various amplitudes and rates of the magnetic field change (quench velocity) during the energy removal.

The method was developed of magnetic induction calculation in the solenoid centre at the beginning of the quench under various initial experimental conditions. It is shown that under definite conditions the quench induction (i.e., the induction at the beginning of the quench is indepedent of the velocity of energy removal.

HEATING UP OF THE SUPERCONDUCTOR OF THE HCD WINDING DUE TO THE LOSSES IN THE CHANGING MAGNETIC FIELD

During the energy removal from the SM the magnetic field decays at a rate determined by the SM and protection device parameters. In the case of a linear dump resistor the magnetic field is changing in the manner near to an experimental one

$$B = B_m e^{-t/t_o}; \qquad t = L/R(t), \tag{1}$$

where L is the SM inductance and R(t) is the total ohmic resistance of the circuit. The complete exponential law is determined by the mutual inductance coefficient of the cryostat and SM, time of the current decay in the cryostat, operating rate of the commutating element. In the composite superconductor magnet winding the hysteresis and eddy current losses are generated owing to changing magnetic field. If the screening effect to external magnetic field inside the composite superconductor due to induced screening currents is not essential, the eddy current losses per unit volume of the superconductor under the exponential magnetic field decay are given by [3]

$$W_e = B_m^2/\mu_0 (1 + t_0/\tau); \quad \tau = \frac{\mu_0}{2}\left(\frac{\ell_p}{2\pi}\right)^2 \frac{1}{\rho_e}, \tag{2}$$

ℓ_p twist length, ρ_e specific transverse resistivity of the composite superconductor.

In this case hysteresis losses per unit volume of superconductor per cycle are independent of the rate and mode of change of the field applied

$$W_h = \int \Lambda M(B)\, dB, \tag{3}$$

$M(B)$ is magnetization of the composite superconductor.

The value of these losses is determined by the $J_c(B)$ dependence only [4]

$$dW_h = \frac{2}{3\pi}\mu_0 d J_c(B)\,[1 + (J_{tr}/J_c(B))^2]\, dB, \tag{4}$$

d is filament diameter; J_c critical current density of the composite superconductor; J_{tr} transport current density.

For the type II superconductors (technical ones), according to Kim model [5], the critical current density dependence on the local magnetic field can be written as:

$$J_c(B) = J_0 B_0/(B + B_0), \tag{5}$$

J_0, B_0 are constants for a given superconductor. As the induced screening currents in the outer filaments situated in the changing magnetic field reach their critical value, the magnetic field inside the composite superconductor begins to be screened by induced currents. This takes place under condition $\dot{B} \geq \dot{B}_c$ [4] with

$$\dot{B}_c = 2\rho_e J_c d \lambda^{1/2} / \ell_p^2. \tag{6}$$

λ is filling factor of the composite superconductor. Thus

the magnetization of the twisted composite superconductor can be written as:

$$\dot{M}(B) \simeq M_0 \left[1 + \frac{8}{3\lambda^{1/2}} \frac{\dot{B}}{\dot{B}_c}\right] \tag{7}$$

with $M_0 = \frac{2}{3\pi}\mu_0 d J_c(B)$. As a consequence, the losses per unit volume of the superconductor determined by the term (3) begin to be dependent on the external magnetic field change rate:

$$W(\dot{B}) = \int \Lambda M(B, \dot{B})\, dB. \tag{8}$$

At a field change rate greater than $\dot{B}_c^x$ [6] with

$$\dot{B}_c^x = \dot{B}_c D \lambda^{1/2}/d, \tag{9}$$

D is composite superconductor diameter, the composite superconductor will behave as if the superconductive filaments were "smudged" through the composite superconductor cross section, i.e., it can be considered as a single superconductor with a diameter equal to $D\lambda^{1/2}$. Thus the hysteresis losses per unit volume of the superconductor can be written as

$$dW_h = \frac{2}{3\pi}\mu_0 \lambda^{1/2} D J_c(B)\,[1 + (J_{tr}/J_c(B))^2]\, dB. \tag{10}$$

The Kim model formula [4] holds under the isothermic conditions, however, under adiabatic ones it is necessary to take into account the critical current temperature dependence. Hampshire et al. [7] proposed this dependence to be written as:

$$J_c(B, T) \simeq \frac{J_0 B_0}{B + B_0}\left(1 - \frac{T - T_b}{T_c - T_b} \cdot \frac{B_{c2}}{B_{c2} - B}\right), \tag{11}$$

T_b is bath temperature; T_c, critical temperature at $B = 0$; T, sample temperature; B_{c2}, upper critical magnetic field; J_0, B_0, constants for a given superconductor at $T = T_b$.

For the sample examined $Nb_{0.5}Ti_{0.5}$ ($T_c = 9.2$ K; $B_{c2} = 10.1$ T) the critical current density determination according to formula (11) gives 10% error provided each 0.5 T magnetic field interval sets up other J_0 and B_0 constants.

Term (10) for the hysteresis losses in the case of an adiabatic process leads to

$$dW_h = \frac{2}{3\pi}\mu_0 \lambda^{1/2} D J_c(B,T)\,[1 + (J_{tr}/J_c(B,T))^2]\, dB, \tag{12}$$

where $J_c(B,T)$ is determined by the term (11).

Eddy current losses in the normal metal matrix related to unit volume of the superconductor can be expressed [4] as:

$$dW_e = \frac{1}{\rho_e}\left(\frac{\dot{B}\ell_p}{2\pi}\right)^2 dt\,. \qquad (13)$$

EXPERIMENTAL RESULTS

The experiments were carried out on the laboratory high current density superconducting solenoid [2] (B_0=8 T; I_c=150 A; J_c=0.8÷2.3 10^8 A/m^2; W = 50 kJ, L = 5 H). The solenoid consists of 7 sections wound from multifilamentary composite superconductors NbTi with a copper matrix 0.7, 0.85 and 1.20 mm in diameter, filling factor λ = 50%, twist length being ~25 mm and filament diameters of 65, 75 and 110 μm. The energy removal was carried out using the linear ohmic dump resistor (R_0=const) 0.5 ÷ 7.0 Ω, as well as the suppression arc chamber, connected to a magnetic field suppression device [11] (U=const). The beginning of the magnet going normal during the energy removal process was registered by a detector unit based on a bridge scheme with an accesory coil. A signal from the diagonal of the bridge scheme after its amplification was selected according to its amplitude and time interval in order to avoid the flux jump signals, as well as the interferings signals. The selector unit was adjusted on the amplitude of a voltage signal of 50÷100 mV and a time interval of 1÷10 msec.

The magnetic induction in the centre of the solenoid at the beginning of quench B_q was experimentally investigated as a function of the starting value of the magnetic induction B_s and the change rate of the magnetic field $\dot{B}$ during the energy removal.

In Fig. 1 the dependence of B_q on $\dot{B}$ taking parameter of B_s into account is presented. From these dependences an inte-

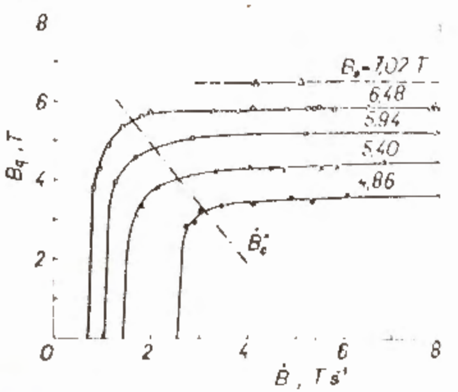
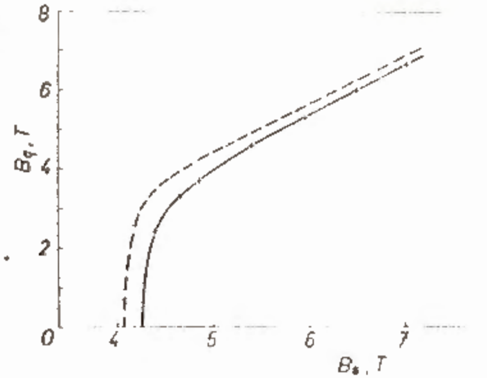


Fig.1. The quench magnetic induction of the solenoid against the magnetic field change rate (magnetic induction decay velocity) at various initial values of induction in the solenoid centre.

Fig.2. A comparison of the measured quench induction of the solenoid with calculated values as a function of initial induction in the solenoid centre. Full line curve - experimental values; dotted line curve - calculation values.



resting experimental fact follows, i.e., for each value of B_s there exists a definite value of $\dot{B}^x_{c}$, starting from which there is a slight dependence of B_q on $\dot{B}$ only.

Full line curve in Fig.2 illustrates an experimental dependence of B_q on B_s, when $\dot{B} \gg \dot{B}_c$ (i.e., $\dot{B}$ = 7÷8 T/sec). By taking B_q values at a maximal field change rate (maximum quench valocity in Fig.1) we shall be able to approach the experimental conditions to an adiabatic ones in the best way.

QUENCH MAGNETIC FIELD LEVEL CALCULATION
UNDER VARIOUS ENERGY REMOVAL CONDITIONS

Provided the heat exchange between the copper matrix and NbTi filaments is ideal the heat balance in the superconducting composite during the energy removal under adiabatic conditions is given by

$$[(1-\lambda)\gamma_{Cu}\cdot c_{Cu} + \lambda\gamma_{NbTi}c_{NbTi}]\,dT = dW_h\,\lambda + dW_e\,, \qquad (14)$$

c is specific heat; γ, specific mass; dW_h, hysteresis losses per unit volume of the superconductor; dW_e, eddy current losses per unit volume of the composite. Specific heat temperature dependence of $Nb_{0.5}Ti_{0.5}$ in the superconducting state obey the following rule [8]

$$c = \beta T^3, \qquad (15)$$

β is constant, for $Nb_{0.5}Ti_{0.5}$ ($\beta = 7\cdot10^{-3}$ mJg^{-1} K^{-4}). We took into account the specific heat dependence on magnetic field, which represents in the induction range 4÷8 T an average increase of 45% in comparison with zero field level value [9]. Specific heat of the copper is chosen as an average value within each temperature interval of a length of 0.5 K.

The inside layers of the winding, situated at the maximum field value are wound from the superconductor of the largest diameter ($D = 1.2$ mm), thus during the energy removal process the maximum amount of heat is generated just in these layers. For the composite superconductor of the inner section of the magnet ($Nb_{0.5}Ti_{0.5}$; $D = 1.2$ mm; $d = 110\ \mu m$; $\lambda = 0.5$; $\ell_p = 25$ mm; $\rho_m = 2\cdot 10^{-10}\ \Omega m$) an estimate, derived wlth formula (9) shows, that in the range $\rho_{e\,min} \simeq \rho_m (1-\lambda)/(1+\lambda) = 0.7\cdot 10^{-10}\ \Omega m \div \rho_{e\,max} = \rho_m (1+\lambda)/(1-\lambda) = 6\cdot 10^{-10}\ \Omega m$ [10] at velocities $\dot{B}_c^x \sim 0.3\div 2.5$ T/sec a full flux penetration of the composite superconductor is expected to start. Consequently, the hysteresis losses per unit volume of the composite superconductor are determined by using formula (12). As the eddy current losses at $\dot{B} > \dot{B}_c^x$ according to our guess represent about 10% of hysteresis losses (12) we shall not account them in the next calculation. This simplification was done, due to the difficulty to determine the specific transverse resistivity of the composite superconductor, which is necessary to know for eddy current losses calculation. The temperatire rise of the composite as it follows from terms (14) and (12) related to the field decay is given by

$$\frac{dT}{dB} \simeq \frac{2}{3\pi}\mu_0 D \lambda^{3/2} \frac{1}{(1-\lambda)\gamma_{Cu} c_{Cu} + \lambda\gamma_{NbTi}\beta T^3} J_c(B,T)\left[1+\left(\frac{I_{tr}(t)}{I_c(B,T)}\right)^2\right]. \qquad (16)$$

Composite superconductor will turn to normal at the moment, when the critical current $I_c(B,T)$ changes in accordance with the temperature rise and the field decay reaches the transport current value $I_{tr}(t)$. According to equation (16) a computer program has been written to calculate the quench magnetic induction level. The results are presented in Fig.2 (dotted line). Some deviations between the calculational and experimental values are probably due to non-totally adiabatic experimental conditions. The analogous calculation for other sections of the winding have been done. As a result of this calculation a highest probability of the quench of the inner section of the winding due to losses has been shown. From equation (16) there follows the independence of a quench magnetic induction value of a magnetic field change rate at a full penetration of the composite, i.e., at $\dot{B} > \dot{B}_c^x$. As it has been noted formerly our guess of $\dot{B}_c^x$ is in the range 0.3÷2.5 T/sec. Similar saturation effect (full flux penetration) was observed experimentally, as it is shown in Fig.1.

Fig.3. Calculated values of the losses per unit volume generated in the composite superconductor of the inner section against initial magnetic induction in the solenoid centre. Full line curve - adiabatic conditions, dotted line curve - isothermic conditions.

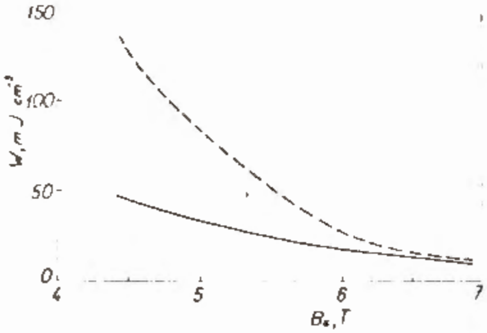
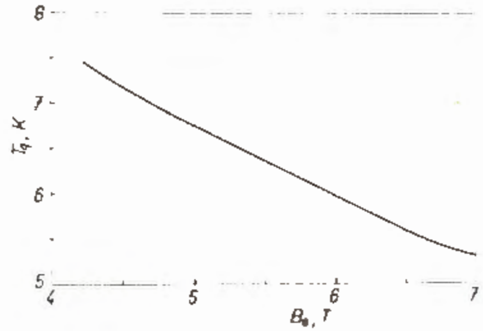


Fig.4. The temperature of the composite superconductor at the beginning of quench as a function of initial magnetic induction in the solenoid centre.



A certain, not essential increase at $\dot{B} > \dot{B}_c^x$ can be explained by not totally adiabatic conditions of the process, as well as by the contribution of the eddy current losses. Thus an increase of quench velocity at $\dot{B} > \dot{B}_c^x$ affects the losses weakly only, as at the same time the effectively of the energy removal goes up [2].

Using (12) a calculation has been done of the losses per unit volume in the composite superconductor under adiabatic conditions and at $\dot{B} > \dot{B}_c^x$ in the time interval from the starting point of the energy removal to the moment of the quench as a function of the initial magnetic induction in the centre of the solenoid. Results are shown in Fig.3 by a full line curve. The losses under isothermic conditions have been calculated and are given in Fig.3 by a dotted line curve, to enable their comparison.

The temperature of the composite superconductor at the beginning of the quench has been calculated as a function of initial values of the magnetic induction in the solenoid centre. Results are shown in Fig.4.

CONCLUSIONS

1. The method of specific losses calculation, as well as of calculation of the temperature rise of the composite superconductor in the time interval from the beginning of the energy removal to the start of the quench under adiabatic conditions has been developed in the form of the computer program.

2. Using the computer program it has been shown the possibility of the quench of a high current density laboratory solenoid during the energy removal due to losses generated in the solenoid winding.

3. The experiments carried out on the laboratory solenoid with a nearly adiabatic insulated winding and storage energy 50 kJ at critical current are in good agreement with calculated results.

4. Both experimental and calculational results nearly demonstrate the independence of the quench magnetic field level of magnetic induction change rate (field decay velocity) at $\dot{B} > \dot{B}_c^x$ (i.e., $\dot{B} \gtrsim 2.5$ T/sec). It is a function of the composite superconductor properties and initial magnetic induction.

ACKNOWLEDGEMENTS

We are greateful to N.G.Anishchenko and R.Luedemann for granting a part of experimental material.

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Received by Publishing Department
on February 28 1980.