Transition currents of superconducting magnet system

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The normal transition of a superconducting magnet system with stored energy 0.5 MJ and power output up to 1 MW has been investigated. It is shown that normal transition is initiated by thermomagnetic instability of the superconducting state which occurs in the second layer of the winding. The theory enables quantitative calculation of the transition current of the magnet if the parameters of the superconductor and characteristics of the magnet are known.

Keywords: superconducting magnets; transition currents; superconductor stability

The normal transition of a superconducting magnet may be initiated by the instability of the superconducting state. This instability develops in the winding in transient regimes at certain definite values of transport current, $I_{(t)}$, and magnetic field, $B_{(t)}$. In the present work the transition current, I_m, of the superconducting magnet system has been measured and calculated theoretically. The calculations are based on the assumption that the normal transitions are initiated by thermomagnetic instability[1,2].

Experimental set-up

The magnet considered is a one-section solenoid wound with multifilamentary Nb–Ti composite wire. This wire comprises 4536 24 μm diameter filaments in a Cu–CuNi mixed matrix. The diameter of the wire is 3.94 mm. The surface of the wire is covered by organic insulation of thickness of the order of 500 μm. The winding of the magnet has an external diameter of 0.54 m, an internal diameter of 0.22 m and a height of 0.73 m. This winding has a layered structure and special channels are provided to feed liquid helium to each part. The former of the coil and other structural elements are made of insulating material (fibre epoxy) to ensure magnet operation up to 50 kV. At $I = 1.1$ kA the stored energy of the magnet is 0.5 MJ and the maximum magnetic field is 4.44 T. The coil inductivity is 0.83 H. To reduce the heat flux from the current leads gaseous helium is used for cooling of the inlets. Details of the conductor and magnet construction are described in References 3 and 4.

To realize different regimes of magnetic system operation the inversion substation of MHD[5] was used. A schematic of the apparatus used for measuring the maximum current of the magnet is shown in *Figure 1*.

In the experiments the time dependences of the current, $I_{(t)}$, magnetic field, $B_{(t)}$, and electrical voltage, $U_{(t)}$, at the ends of each layer of the winding were measured. The measurements of $U_{(t)}$ allow one to obtain the values of I, B, $\dot{I}$ and $\dot{B}$ at the beginning of the instability, and to find the layer of winding in which the transition first occurs. The electrical set-up of the magnet and the protection system permit energy discharge during the normal transition and there was no damage to the magnet

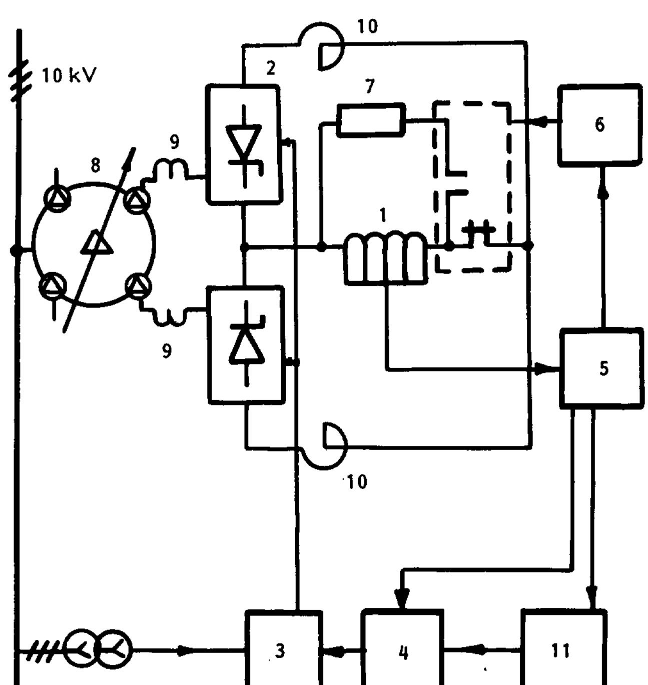

Figure 1 Schematic of the apparatus used for measuring the maximum current. 1, Superconducting coil; 2, 1.7 MW thyristor converter ($I_{max} = 1.2$ kA, $U_{max} = 1.4$ kV); 3, automatic current control system; 4, current and voltage recorder; 5, quench detector; 6, control of d.c. breaker; 7, dump resistor ($R = 1\ \Omega$); 8, delta–delta connected transformer; 9, 10, inductive coils; 11, computer monitoring of the system

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in these experiments. The relation between the transport current, $I_{(t)}$, and the magnetic field, $B_{(t)}$, at the coil axis takes the form: $B_{(t)} = kI_{(t)}$, where $k = 4.22 \times 10^{-3}$ T A^{-1}.

Results and conclusions

The form of the current pulse produced by the current supply is shown in *Figure 2*. The initial value of the current is I_0. Then it rises to I' in the time interval Δt_1 (charge of the magnet). The current remains constant for the time interval Δt and then decreases to some value I during time Δt_2 (discharge). The power input reaches 0.6 MW during charge (at higher values of power the normal transition occurs) and the normal transition does not occur at power output up to 1 MW during discharge.

The results of the experiments for the regime of magnet excitation are shown in *Figure 3* for rather high $\dot{I} = (I' - I_0)/\Delta t_1$ ($\dot{I} > 500$ A s^{-1}) at $I_0 = 0$. Each point represents the experiment in which a given value of I' has been attained at a given value of $\dot{I}$. The dashed line ($I' = I_m(\dot{I})$) separates the stable regimes (triangles) from the unstable (crosses). Analysis of the signal $U_{(t)}$ has shown that the normal transition occurs first in the second layer of the winding where the values of B and $\dot{B}$ are almost as large as in the first layer, but where the heat removal is slightly lower.

The normal transition was not observed in these experiments with current decrease, although in this regime the current decreases from $I' = 1$ kA to $I = 0$ at rates up to 1.3 kA s^{-1}.

To find the theoretical dependence $I_m(\dot{I})$ the theory of superconducting state stability with respect to small disturbances will be used. This theory predicts that the superconducting state in composite superconductors is stable if the level of heat release due to the small perturbations of temperature, δT, electric field, δE, and magnetic field, δB, is lower than the level of heat transfer to the coolant, i.e.

$$\int_A j\delta E dA < \int_P^Q W\delta T dP$$

where: $A = \pi d^2/4$ = cross-sectional area of the conductor; d = conductor diameter; $P = \pi d$ = perimeter of the conductor cross-section; $j = 4I/(\pi d^2)$; and W = heat transfer coefficient. The above inequality allows one to

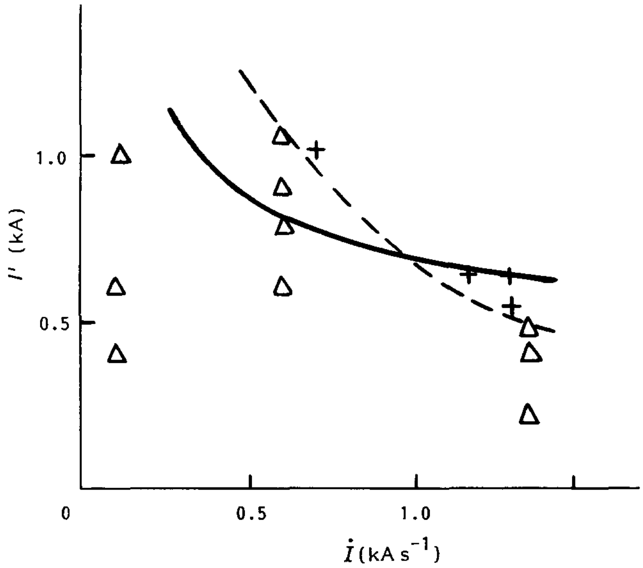

Figure 3 Results of measurements of I' ($\dot{I}$). △, Stable regimes; +, unstable regimes; ----, interface between stable and unstable regimes; ——, theory

obtain the superconducting state stability criterion in the following form[1,2,6]

$$\langle E_{\parallel} \rangle < E_c = \frac{\pi d W I_1(T_c - T_0)}{I_s^2} \tag{1}$$

where: $\langle E_{\parallel} \rangle$ = longitudinal (along the filaments) component of the electric field in the composite averaged over the cross-section of the conductor; $T_c = T_c(B)$ = critical temperature; T_0 = coolant temperature; $I_s = I_s(B)$ = critical current; $I_1 = I_1(B)$ = parameter of the current–voltage characteristic of the composite at $T_0 < T_c$. Then

$$I(E_{\parallel}) = I_s(B) + I_1(B)\ln(E_{\parallel}/E_0) \tag{2}$$

The electric field, E_0, is defined by the condition $I(E_0) = I_s(B)$. To calculate I_m one has to find $\langle E_{\parallel} \rangle$ as the function of I, $\dot{I}$, $\dot{B}$, etc.; then the value of I_m is given by the equation $\langle E_{\parallel}(I_m, \dot{I}, \dot{B}, \ldots) \rangle = E_c$.

This method has been applied in previous work[7,8] to calculate I_m in short samples of sufficiently low $\dot{I}$ and $\dot{B}$. In References 7 and 8 an approximate procedure was used to find $\langle E_{\parallel}(I) \rangle$. In the present calculations the case for high $\dot{I}$ and $\dot{B}$ is considered and a more accurate procedure has to be used to find I_m, which takes into account the twisting of the superconductor. The calculation of $E_{\parallel}(I)$ in the twisted superconductor is a rather complicated procedure. It was described in details in previous work[9]. In the present work only the final result is presented. According to Reference 9 the equation for I_m may be written in the form

$$-i_m - \ln(1 - i_m) + 0.42\frac{\pi d \dot{B}}{\mu_0 \dot{I}} \times \frac{1.5 i_m - 1 + (1 + i_m)^{3/2}}{1 - 0.5 i_m} = \frac{4\pi E_c}{\mu_0 \dot{I}} \tag{3}$$

where $i_m = I_m/I_s$ and E_c is defined by Equation (1). Equation (3) is valid if the twist pitch, L, is small enough, i.e. $\tau_0 \dot{B} \ll B$, $\tau_0 \dot{B} \ll \mu_0 I_s/d$, where τ_0 is the characteristic time of the resistive current decay in the twisted composite

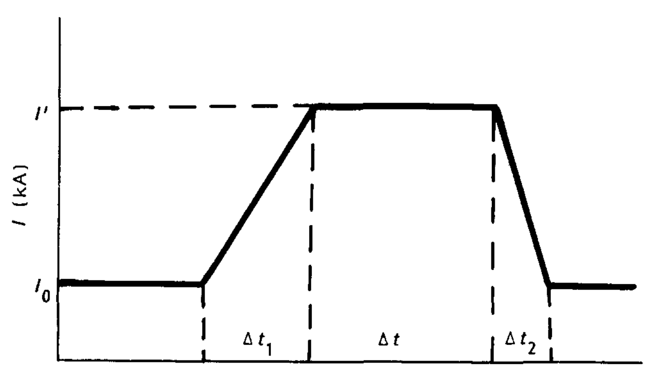

Figure 2 Current pulse $I_{(t)}$

and $\tau_0 = \mu_0 L^2 \sigma_\perp / 8\pi^2$ (see Reference 10), and $\sigma_\perp$ is the transverse conductivity of the normal matrix.

The dependences $I_s(B)$ and $I_1(B)$ have been measured in short samples using standard methods[7,8] and may be approximated by the formulae

$$I_s(B) = (3.44 \times 10^4 A/T)/(B + 3.31\ T)$$
$$I_1(B) = (7.76 \times 10^2 A/T)/(B + 3.96\ T) \tag{4}$$

The value $W = 70$–$75\ \mathrm{W\,m^{-2}\,K^{-1}}$ was obtained following Reference 6 and $\tau_0 = 2.5$ ms was determined from the a.c. loss measurements[10]. The conductor diameter, $d = 3.94$ mm and $T_c(B)$ for Nb–Ti may be approximated from the formula $T_c = (9.3 - 0.47\,B)$K, where B has to be expressed in T.

Substituting the values described above into Equation (3) and using the relation $B = kI$, one can calculate numerically the curve $I_m(\dot{I})$. This curve is shown in *Figure 3* by a solid line for $\dot{I} > 300\ \mathrm{A\ s^{-1}}$. The maximum difference between the theory and actual measurements is less than 25% in the interval of $\dot{I}$ from 500 to 1300 A $\mathrm{s^{-1}}$. The discrepancy between the theory and experimental results decreases at lower $\dot{I}$ (the data will be published elsewhere). One can readily verify that $\tau_0 \dot{B} < 0.01$ T and that the applicability conditions of Equation (3) are fulfilled in the present experiments. Note that no adjusting parameters are used.

To find I_m during discharge of the magnet one has to find $E_\parallel(I)$ in the case of a monotonic decrease of $I_{(t)}$ and $B_{(t)}$. It can be verified that under this condition the equation for the transition current, I_m, may be presented in the form of Equation (3) with $i_m = (I' - I_m)/2I_s$. It is found that with current decrease the instability occurs at I' and $\dot{I}$ rather higher than with current increase. Note, that $I_m \approx 0.1 - 0.2 I_s$ and I_m is considerably higher than the normal zone minimum propagating current, I_p ($I_p \approx 300$ A at $B = 4$ T).

Thus, it can be concluded that the normal transition of the superconducting magnet has been initiated by the thermomagnetic instability of the superconducting state at some part of the winding. The theory allows us to find the current at which the transition occurs.

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