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Fundamental characteristics of wires for controlled superconducting windings

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The performance (stability) of superconducting wires is ensured by smearing of their transient characteristics. The same important property can be used to create reliably controlled superconducting non–degrading windings. The transition to the normal state of such windings is preceded by the appearance of an electric voltage in the area located in the maximum magnetic field. The more smeared is the wire transient response, the greater is the magnitude of the stable voltage.

Keywords: laminar windings, controllability, non–isothermal current–voltage characteristic, feedback.

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An unfortunate feature of up–to–date superconducting magnets (non–stabilized by Stekly [1]) is that their transition to the normal state with increasing current occurs without any preceding evidences, and the only possible control action in this case is urgent extraction of accumulated energy on a signal received from the circuit detecting the presence of the appeared and propagating normal zone. Such an unpredictable transition is being explained by random thermal perturbations that are commonly regarded as inevitable [1]. The unpredictability imparts to the modern technologies for designing superconducting windings a „flavor of adventure“ (for instance, it is planned to ensure protection of the toroidal field winding of the International Thermonuclear Experimental Reactor (ITER) by urgently extracting energy equivalent to 10 t of trinitrotoluene to the external resistor). Elimination of this „flavor“ is an extremely important fundamental and applied task. This goal can be achieved only in windings made free of the above mentioned random perturbations, e. g., in laminar windings. Design principles of such windings, as well as the sources of significant difficulties in creating conventional superconducting magnets, are described in review [2]. This review presents also references to primary literature sources of basic initial assertions used in this work. In laminar windings, the wire is fixed over its entire length on a rigid frame designed for percepting the magnetic force during deformation permissible for the wire (a sufficiently rigid frame prevents deformation of wires sensitive to it). The objective of this study is to demonstrate the possibility of ensuring reliable controllability of superconducting windings with a high design current density due to using wires with calibrated smearing of the transient characteristic.

The wire fundamental characteristic allowing reliable designing of control systems for windings fabricated from this wire is its constitutive relation, i. e. its conductivity dependence on temperature, magnetic field and current. Due to smearing of the superconducting transition, the semiconductor current–voltage characteristic (VAC) has a stable section with the positive voltage derivative with respect to current. The voltage of this section may be used to organize the negative feedback necessary for controlling (in the current control system for the niobium–stanum solenoid [3,4], the stable VAC was measured by using a conventional bridge circuit [1] for revealing the normal zone). This fundamental characteristic has been so far comprehensively studied only for the niobium–titanium and niobium–zirconium wires (NT-50 and NZ-50). To construct the non–isothermal VAC and calculate the current and electric field maximal values above which the uncontrollable quench to the normal state occurs for wires with the copper or other matrix, the transverse component of the conductivity tensor is used, i. e. the wire transient characteristic in the magnetic field perpendicular to the wire axis:

$$\sigma(T, B, I) = \sigma_n^* \left\{ 1 + \exp\left[\left(1 - \frac{T}{T_c^*} - \frac{B}{B_{c2}^*} - \frac{I}{I_{c/2}^*} \right) \frac{1}{\delta^*} \right] \right\}.$$

Here $\sigma_n^* = k_n\sigma_n + (1 - k_n)\sigma_m$ is the wire conductivity in the normal state, k_n is the portion of the wire cross–section occupied by the superconductor, σ_m is the matrix conductivity, σ_n is the superconductor normal–state conductivity, and the standard criterion for finding values of T_c^*, B_{c2}^*, $I_{c/2}^*$ is the fact of reaching by the wire resistance a half of its normal value $(1/\sigma_n^*)$ with varying one of the state parameters (temperature T, field B or current I) at zero values of other parameters. Those critical values are somewhat lower than critical parameters of the superconductor itself because of the presence of the low–normal–resistance matrix $A_c^* = A_c\left[1 - \delta \ln\left(k\frac{\sigma_m}{\sigma_n} + 1\right)\right]$, $k = (1 - k_n)/k_n$. Vice versa, the parameter describing the superconducting transition

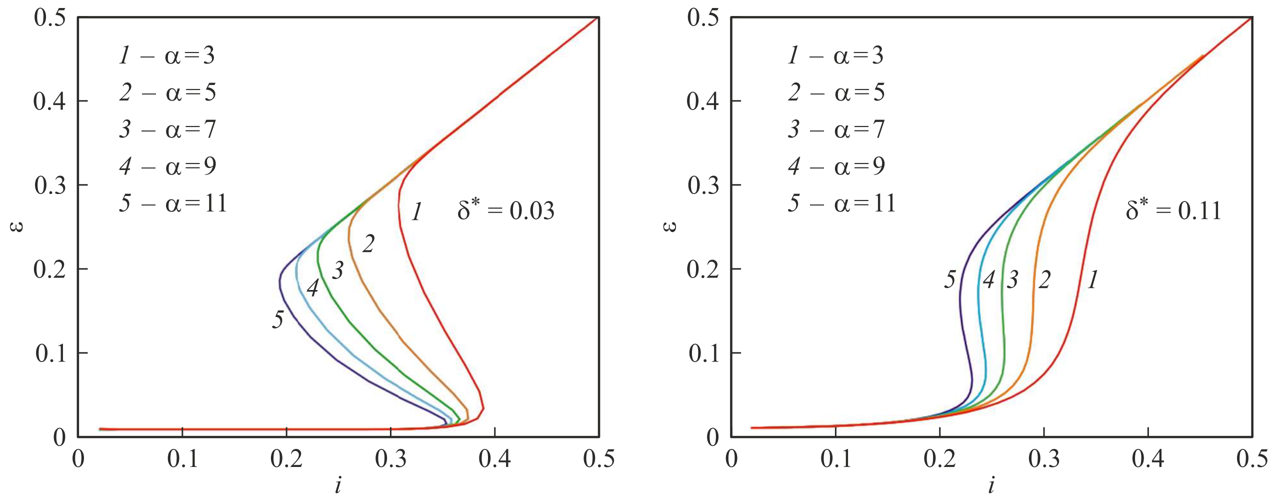

Figure 1. Examples of dimensionless non–isothermal current–voltage characteristics of the wire for a few values of parameters α and δ^* at $b = 0.5$.

steepness,

$$\delta^* = \frac{\delta}{\left[1 - \delta \ln\left(k\,\frac{\sigma_m}{\sigma_n} + 1\right)\right]} > \delta,$$

is somewhat higher than that of the superconductor itself. The dimensionless non–isothermal VAC of the wire expressed in the parametric form

$$\varepsilon = iy, \qquad i = \frac{-1 + \sqrt{1 + 4\alpha y(1 - p - b)}}{2\alpha y},$$

$$y = [1 + \exp(p)]^{-1}, \qquad -1 < p < 1$$

is the solution of the transcendental equation of the stationary balance during heating the wire with its own current

$$-\delta^* \ln(\varepsilon/i) = 1 - \alpha\varepsilon i - i - b,$$

where

$$\varepsilon = \frac{R(T,B,I)I}{R_n I^*_{c/2}},\ i = \frac{I}{I^*_{c/2}},\ \alpha = \frac{R_n I^{*2}_{c/2}}{\lambda S T^*},\ b = \frac{B}{B^*_{c2}},$$

$\lambda S T^*$ is the wire–to–substrate heat flow through the electrical insulation layer, $T^* = T_c(B)$ — T_s is the sample temperature exceedance over the cooling substrate temperature T_s, S is the area of the wire–substrate contact, $R(T,B,I)$ is the constitutive relation. Parameter α is an analogue of the Stekly parameter [1] and differs from it in that it accounts for not the heat removal to boiling helium but for the heat flow through the electrical insulation to the cooled frame on which the superconducting wire is fixed. Fig. 1 presents case non–isothermal VACs for several values of α and δ^*. Each of them possesses a stable initial section terminating at $di/d\varepsilon = 0$. Quench electric field ε_q corresponds to this point. With regard to stability, this field defines the maximal rate of the current distribution alignment over the wire cross–section, while its contribution to the controllability is that it defines the detected voltage maximum in the winding section where the maximum possible stable current is achieved.

Fig. 2 presents the patterns of the i_q and ε_q parameters for practically valuable ranges of the α and δ^* parameters. To obtain the maximum current in amperes, multiply the dimensionless current by critical current $I^*_{c/2}(T_s)$. The electric field is equal to product $\varepsilon R_n I^*_{c/2}$.

Using Fig. 2, it is possible to estimate stable parameters for an arbitrary wire. For instance, for a wire with a rectangular cross–section of 2×3.5 mm at $S_{\text{Nb-Ti}}/S_{\text{Cu}} = 0.6$, $R_n = 5 \cdot 10^{-3}\,\Omega/\text{m}$, $I^*_{c/2}(4.2\,\text{K}, 0\,\text{T}) = 7000\,\text{A}$, $\delta^*(0) = 0.03$, $I^*_{c/2}(4.2\,\text{K}, 5.5\,\text{T}) = 3500\,\text{A}$, $\alpha = 8$ obtain $i_q = 0.68$, $\varepsilon_q = 0.025$. The maximum stable current is $I_{\max} = 2380\,\text{A}$. The quench electric field is $E_q = 0.437\,\text{V/m}$. The easily detectable signal 1 mV/cm will arise at the current of 2070 A.

The Table demonstrates the influence of the extent of the transient characteristic smearing on the achievable values of operating current and detected voltage in two wires differing in only this parameter. One can see that in the wire with a more smeared transition the feedback signal is 26 times higher than that in the competing wire, the technically permissible critical current being retained. Notice also that this wire is significantly more stable [4] than the competing one, since its current density distribution over the cross–section gets uniform 26 times faster. The transient characteristic smearing allows selecting the optimal ratio between the operating current and detected voltage with retaining some margin relative to the uncontrollable transition current. In designing superconducting windings, the wire specifications should include, in addition to the critical current, the necessary extent of the superconducting transition smearing defining both the wire stability under specific conditions and necessary sensitivity of the control system. The development of techniques for controlling the

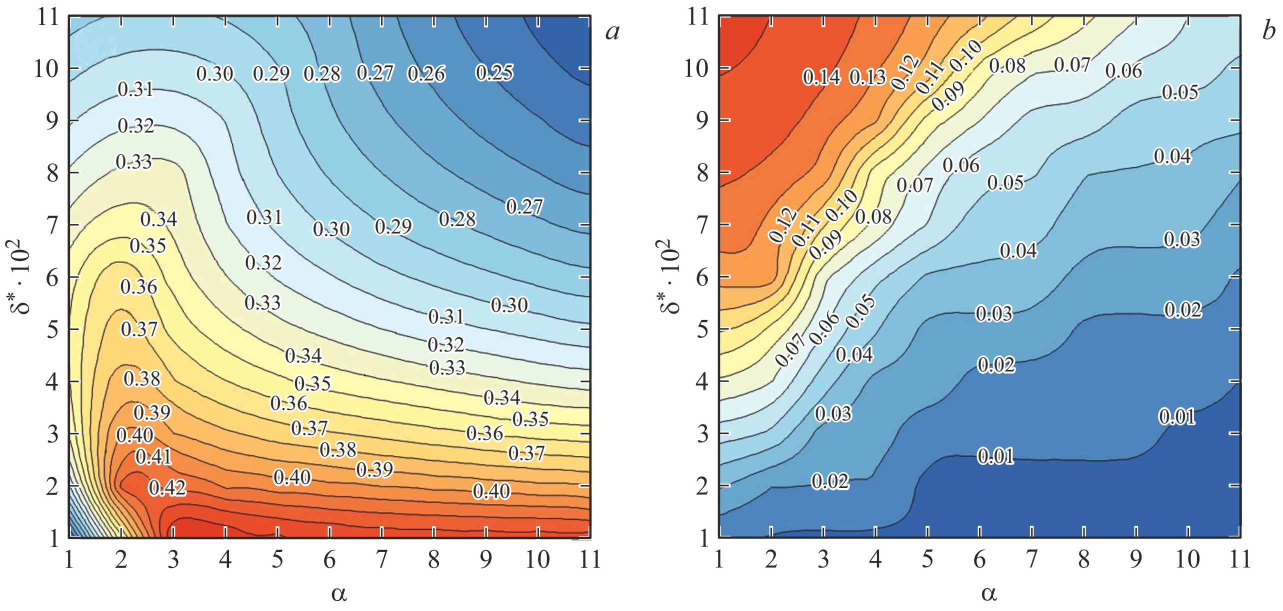

Figure 2. Maximum dimensionless values of the stable current (a) and electric field (b) versus parameters α and δ^* at $b = 0.5$.

Estimates of the maximal ($I_{\max}$) and operating (I_{oper}) currents and respective electric fields (E_q and E_{oper}) in the wire with cross−section of 2×3.5 mm ($R_n(4.2) = 5 \cdot 10^{-3}$ Ω/m) in the magnetic field of 5.5 T

$I^*_{c/2}$ (0 K, 0 T), A	$I^*_{c/2}$ (4.2 K, 0 T), A	α	δ^*	$I_{\max}$, A	E_q, V/m	I_{oper}, A	E_{oper}, mV/m
13000	6890	8	0.06	2050	0.906	1637	122
13000	6890	8	0.01	2480	0.034	2411	4.7

transition smearing is a new task for superconducting wires product engineers.

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Conflict of interests

The author declares that he has no conflict of interests.

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