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Influences of voltage–current characteristic difference on quench development in low-T_c and high-T_c superconducting devices (Review)

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Abstract

We review the approaches in analysis of quench development in LTS and HTS superconducting devices. Considering description of quench from very general point of view, we analyze how the change from sharp voltage–current characteristics with high-index n to smooth characteristics with low n and other material parameters affects quench dynamics. We compare traditional approaches for the description of the quench development in LTS devices with new approaches suggested for HTS devices. Reduction of index value n and high-operating temperature leads to a change of the quench development time, temperature rising rate that make it unnecessary to use the term "normal zone propagation" for describing quench in HTS devices.

Keywords: Superconductivity; Voltage–current characteristics; Quench

1. Introduction

The superconducting state is a meta-stable state [1] that means one can expect the transition from superconducting to normal state caused by some disturbances. Quench, as we call it, always is present in the life of any designer of any superconducting device both, low and high T_c [1,2]. In any quench analysis two major questions are: what will be maximum temperature T_{max} and voltage V_{max} developed during quench of a superconducting device and how quickly these values will be achieved or quench time t_q. All quench analysis approaches should answer these questions.

Discovery of high-temperature superconductors (HTS) and development of technology of HTS current carrying elements (tapes or wires or cables) paved the way for creation of new superconducting devices operated at temperatures up to ~80 K. In the very first studies it was shown that HTS devices are much more stable and quench rarely happens there. But with rise of sizes of HTS

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devices the problem appeared. In some cases unlimitedly rising temperature was observed in HTS devices, while the rate of this thermal runaway was slower than in LTS devices [3–7]. So, the task to understand and to describe quench in HTS devices is still important.

The basic equation describing the quench process in HTS and LTS superconducting devices is the same, but their quench development behavior is quite different. These differences come from the difference in voltage–current characteristics (VCC), specific heat at operation temperature, temperature interval over which the device remains superconducting and critical temperature. All of the above strongly affects the quench behavior of HTS devices.

In this paper we review the approaches in analysis of quench development in LTS and HTS superconducting devices. Considering quench from very general point of view, we analyze how the change from sharp VCC with high-index n to smooth characteristics with low n and other material parameters affects quench dynamics. We compare traditional approaches for the description of the quench development in LTS devices with new approaches suggested for HTS devices [3,8]. Low-index value n and high-operating temperature leads to a change of the quench development time, temperature rising rate and even eliminate the term of "normal zone propagation" commonly used for describing quench in LTS devices.

2. General description

The general, simplified, one-dimensional differential equation that governs the quenching process in any superconductor is given by [9,10]:

$$C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + Q(T) - W(T), \qquad (1)$$

where $C(T)$ is the volumetrically averaged heat capacity, the first term on the right-hand side represents thermal conduction along the superconductors, $k(T)$ is the volumetrically averaged thermal conductivity, $Q(T)$ represents the heat generation, particularly due to VCC. The last term represents the cooling, that is usually linear in temperature [2,11].

The traditional presentation of VCC of superconductors $E(I,T)$ is:

$$E(I,T) = E_0\left(\frac{I}{I_0(T)}\right)^n. \qquad (2)$$

Here, n is the parameter called index, $I_0(T)$ is a current corresponded to electric field level E_0 that is usually 1 or 0.1 μV/cm. The current $I_0(T)$ is what we usually call "critical current". In this case heat release term in (1) will look as:

$$Q(T,n) = IE = I_0E_0\left(\frac{I}{I_0(T)}\right)^{n+1}. \qquad (3)$$

Eq. (1) is a basic heat balance equation to evaluate hot spot temperature in superconductors at a quench. This equation is the same for LTS and HTS superconductors. Generally, this equation should be solved numerically, because of non-linearity and complexity of all terms included. But for practical purposes some simplified models were developed permitting well-justified analysis of quench development in superconducting devices. Let us consider these models.

2.1. LTS superconducting devices—normal zone propagation

A superconductor, carrying transport current, can be in a stationary state if there is a balance between cooling and heat release. Typical calculated temperature dependencies for heat release $Q(T,n)$ and for cooling $W(T)$ for hypothetical superconductors with different n values are shown in Fig. 1. One can see that there are three temperature points of balance $T_{\text{stab-min}}$, $T_{\text{stab-max}}$ and $T_{\text{non-stab}}$. First two points are stable ones corresponding to superconducting and to normal state. The third point is non-stable.

The superconducting state may be destroyed by a disturbance, which cause the sufficient part of the sample volume overheating up to the temperatures $T > T_{\text{non-stab}}$ [2,11]. One can see that for high n-value, typical for LTS, this disturbance could be small enough because necessary temperature rise is rather small. As a result, very small heat pulses

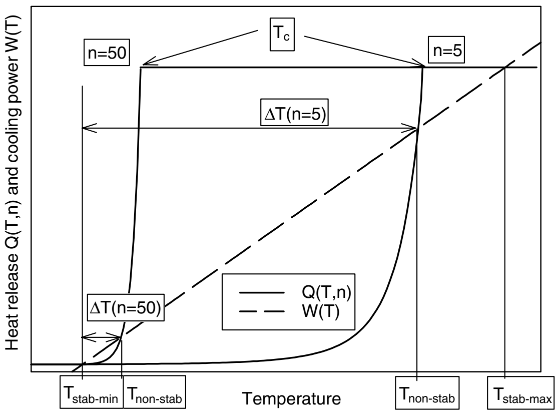

Fig. 1. Cooling and heat release vs. temperature for superconductors with different *n*-value.

(due to disturbances of magnetic, thermal or mechanical natures) may give rise to the local normal phase nucleation and its propagation over the sample if the transport current is not too low [2,11]. This happens because of the sharp slope of $Q(T,n)$ curve (see Fig. 1) that permits quick switch between superconducting ($T_{\text{stab-min}}$) and normal ($T_{\text{stab-max}}$) state with the existence of rather clear borders between states [2,11,12].

To the contrary, much larger external power requires for local overheat or instability initiation for superconductor with low *n*-value (typical for HTS). Normal zone with sharp borders may not appear during the entire quench development process [3,4,13].

In reality, the situation is aggravated much more by the high-specific heat $C(T)$ for HTS devices operating at temperature range 20–80 K. Specific heat for HTS is by 1–3 orders of magnitude higher than at helium temperatures. The dynamic of the normal transition is characterized by the thermal time [12]:

$$t_{\mathrm{h}} = \frac{CA}{Ph}, \tag{4}$$

where A is the conductor cross-section area, P is cooling perimeter and h is heat removal coefficient. In the case of high temperatures this time is larger than at helium temperature. So, the transition processes in HTS develop much more slowly.

So, due to sharp (high *n*-value) VCC and low $C(T)$ fast thermal instability happens in LTS with appearance of clearly determined and propagating normal zone. The model with appearance of normal zone and its propagation is well justified to analyze quench in LTS devices [2,11,12]. While for HTS device other approaches should be found [3]. We will consider them below.

There is well known, approach to find maximum temperature during quench by comparison of adiabatic heat release due to Joule heating with the heat capacity of a device, i.e. [14]:

$$\int_0^\infty J^2(t)\,\mathrm{d}t = J_0^2 t_{\mathrm{d}} = \int_{T_0}^{T_{\max}} \frac{C(T)}{\rho(T)}\,\mathrm{d}T = U(T_{\max}), \tag{5}$$

where $J(T)$ is the current density, $\rho(T)$ is the resistivity, J_0 is the initial current density and t_{d} is the characteristic time for the current decay caused by any reason (magnet self-discharge, power supply shutting down, etc.). All quantities are averaged over the winding cross-section. Value $F_{\mathrm{q}}(J_0) = J_0^2 t_{\mathrm{d}}$ is called the quench load. For a given superconducting winding the function $U(T_{\max})$, called "quench capacity", contains only the properties of materials used in the winding, may be used to estimate the maximum temperature $T_{\max}$ if one knows time t_d. Actually, (5) is valid for any superconducting device (LTS and HTS) in adiabatic conditions and could be considered as maximal estimation of the temperature of heating.

Quick transition (one can neglect the switch time from superconducting to normal state) permits to find the traveling wave solution of Eq. (1) that gives the speed with which a traveling temperature wave carries the heat along the conductor [2,12]. The quench development in LTS devices can be well modeled by a normal volume propagated, in general case, in three dimensions. Analyses of quench to find t_d (or t_{q}) value and, therefore, $T_{\max}$ and $V_{\max}$ [2,11,15,16] usually consider extending normal volume due to normal zone propagation, energy released in this volume and current decay in a superconducting device (usually magnet) on the extended normal resistance. The well-known analysis of Wilson [2] gives estimations for the decay time [2]:

$$t_q \sim \left[\frac{LU_0^2}{J_0^4 \rho_0 v^3}\right]^{1/6} \sim J_0^{-23/6} \approx J_0^{-4}. \tag{6}$$

Here L is the inductance of a magnet, v is the normal zone propagation velocity, ρ_0 and U_0 (resistivity and quench capacity at some characteristic temperature) are the adjusting parameters, J_0 and I_0 are the initial current density and initial current correspondingly.

We would like to call your attention to much less known analysis by late Russian theoretic Rusinov [15,16] that was well justified and confirmed by experiments for tight windings with copper matrix. This analysis provides the following expressions for t_d:

$$t_d \sim \tau_h \ln(\gamma/2) \sim \frac{2\ln I_0}{I_0^2}, \quad \tau_h \sim \frac{w_0}{\rho_0 I_0^2},$$
$$\gamma \sim \frac{LI_0^2/2}{\Omega_n(\tau_h) w_0}. \tag{7}$$

Here $\Omega_n(\tau_h)$ is a volume of normal zone filled during characteristic time τ_h; w_0, ρ_0 are the enthalpy and resistivity at initial temperature, and γ is a ratio of the full energy stored in a magnet to the enthalpy of volume $\Omega_n(\tau_h)$ [15,16]. It was shown that the quench and discharge of the magnet could be considered [15,17] as discharging on the constant normal resistance, which is the resistance provided by the volume $\Omega_n(\tau_h)$. It will return correct values for maximum quench load, quench time and voltage. This method was very well confirmed experimentally (see for example [16,17]).

So, there are well-developed approaches to analyze quench in LTS devices based on normal zone propagation model.

2.2. HTS superconducting devices—quasi-uniform heating

In principle, normal zone propagation approach could be applied also for HTS devices. The first attempts were done in [10,11]. On the other hand, it was shown that practically it is quite difficult to distinguish adequately normal and superconducting states in HTS devices. Due to high-specific heat at operational temperatures normal zone propagation velocity is very slow in HTS barely reaching centimeters per second [10,11] compared with tenths of meter per second in LTS. The traditional approach (normal zone propagation) is fair for HTS devices, but rather inconvenient and new approaches were needed to be developed.

Such approach, or thermal quench theory, was developed in detail in [3] and well confirmed by many experiments [4,8,13,20]. The thermal quench is actually slowly developed (unlike in LTS devices) thermal instability, which eventually leads to appearance of normal zone and its propagation. The theory uses the standard power law (2) for VCC of HTS superconductors. It was shown [3] that near the thermal quench current (TQC) I_q, analytical expressions could be found for two cases. If $I < I_q$, the temperature stabilize at some level $T_q - T_f$. If $I > I_q$, the temperature rises with strong acceleration after the time t_q [3,4,8,13,18,19]. The following expressions have been found. Time evolution of temperature and electric field in a HTS device:

$$\frac{T(t) - T_q}{T_f} = \frac{E(t) - E_q}{E_f} = \tan\frac{t - t_q}{t_f}, \quad I > I_q. \tag{8}$$

Threshold thermal quench current (TQC):

$$\frac{I_q}{I_0(T_0)} = \frac{n}{n+1}\left[\frac{hP(T_c - T_0)}{nE_0 I_0(T_0)}\right]^{1/(n+1)}. \tag{9}$$

Characteristic time of the quench development:

$$t_q = t_h\left(\sqrt{\frac{2I_q}{|I - I_q|(n+1)}}\right) \times \arctan\left(\sqrt{\frac{I_q}{2|I - I_q|(n+1)}}\right). \tag{10}$$

Characteristic temperatures and voltages:

$$T_q = T_0 + \frac{T_c - T_0}{n+1}, \quad T_f = (T_c - T_0)\sqrt{\frac{2|I - I_q|}{(n+1)I_q}},$$
$$E_q = \frac{hPT_c}{I_0(T_0)n}, \quad E_f = nE_q\sqrt{\frac{2|I - I_q|}{(n+1)I_q}}. \tag{11}$$

Characteristic time:

$$t_f = t_h\sqrt{\frac{2I_q}{|I - I_q|(n+1)}}. \tag{12}$$

Here T_0 and T_c are the ambient temperature and critical temperature of a superconductor, T_q is a characteristic temperature at which fast temperature rise starts at time t_q, t_f is a time necessary to heat a sample to equilibrium temperature $T_q - T_f$ at $I < I_q$ [1]. t_h is a characteristics thermal time (4). All the above expressions do not have adjusting parameters and were extensively verified by experiments [3,4,8,13,19,20]. It was also shown that expressions (8) for $I > I_q$ are universal and could be scaled for the widest variety of superconducting devices. In Fig. 2 dependencies of dimensionless temperatures and voltages on dimensionless time are shown for different superconducting objects. One can see that the theory well coincides with the experimental data for quite different devices.

The theory [3] has been developed for the uniform heating. However, in a real magnet's cooling, VCC and "critical currents" of the winding material are not uniform over the magnet's volume. To handle such cases, the analysis should start from the evaluation of the characteristic heat length: $l_h = \sqrt{Ak/Ph}$, that is the length through which the temperature is changing along the winding [8]. As heat conductivity is changing little at temperatures 20–80 K, heat length is determined mainly by cooling conditions. It was shown in [8] by comparison of estimated heat lengths with winding characteristic sizes (experimental data were used), that in windings cooled by cryocoolers their sizes are sufficiently less than characteristic length l_h, at least up to 1 m winding sizes. So, cryocooler cooled windings can be considered as quasi-uniform with all parameters averaged along the winding [3,8,20].

So, the first difference one can see in approaches for quench description of LTS and HTS devices is that HTS are considered as quasi-uniform cases without any idea about normal zone and even superconductivity. Just a media with non-linear parameters is considered and "the critical current" is used as a kind of conditional parameter only [3,8,13]. On the other hand, LTS are considered as sufficiently non-uniform with the propagating normal zone. But if to consider uniform heating of superconductors the temperature and voltage rise for LTS conductor will be also determined by Eq. (8). It is illustrated in Fig. 2, where voltage on uniformly quenched LTS NbTi–CuNi wire is shown and it coincides with theoretical calculations by (8) [13].

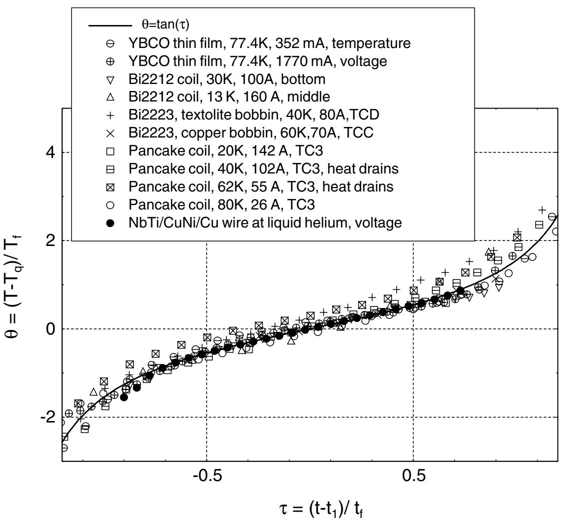

Fig. 2. Dimensionless temperature θ versus dimensionless time τ for experiments with different objects.

3. Comparison of LTS and HTS quench description

3.1. Limitation of the operating current—Design criteria

LTS devices are usually designed to operate at current less than the critical current I_0. It is considered that LTS devices may remain superconducting below this current indefinitely long, unless a strong enough disturbance does quench it. It is so called "critical current design criteria".

On the other hand, from (9) one can see that depending on the winding size (cooling perimeter), cooling conditions and index n, thermal quench current can be more than current I_0 as well as less than this current. Actually, this expression is valid for both LTS and HTS devices, but it is more important for the last ones. Usually thermal quench current becomes less than critical current in large windings, because heat release occurs in a volume and cooling is always from a surface. The ratio surface to volume reduces with the size rise.

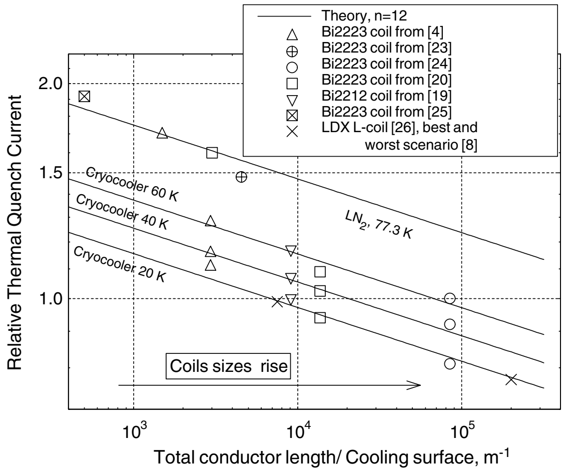

Fig. 3. Relative TQC versus inverse effective cooling perimeter [8]. Symbols are data from different HTS coils from the literature [4,8,19,20,23–26].

Therefore, the thermal quench current determined by this ratio, may become less than the critical current. It means that one has to switch from the "critical current design criteria" to the "thermal quench design criteria" [5,8]. Especially, it is important for large HTS windings. Small HTS windings can operate at current more than critical ones as it was shown in [4,13]. It is illustrated in Fig. 3 were dependencies of relative TQC are shown versus effective cooling perimeter [8]. Experimental data are collected from different works. One can see that thermal quench current decreases with sizes of the windings and calculations well coincide with experiments.

If in expression (9) the n value to increases, one can see that the thermal quench current becomes closer to the "critical current". Also, I_q becomes less than I_0 if operating current density will rise. It is illustrated in Fig. 4, where dependencies of $I_q(n)$ are shown for different current densities. The parameters of cooling and critical currents were taken from the experiments [4,13]. So, if future HTS conductors will demonstrate high n value and high-operating current density, their thermal quench current will be closer to the critical current and the traditional design criteria could be used.

Thus, low n in HTS devices permits them stable operation at current even more than the "critical" one (determined by the certain electric field on a conductor) if other conditions of (9) (good enough cooling and low enough current density) are completed. With n rising, the situation becomes

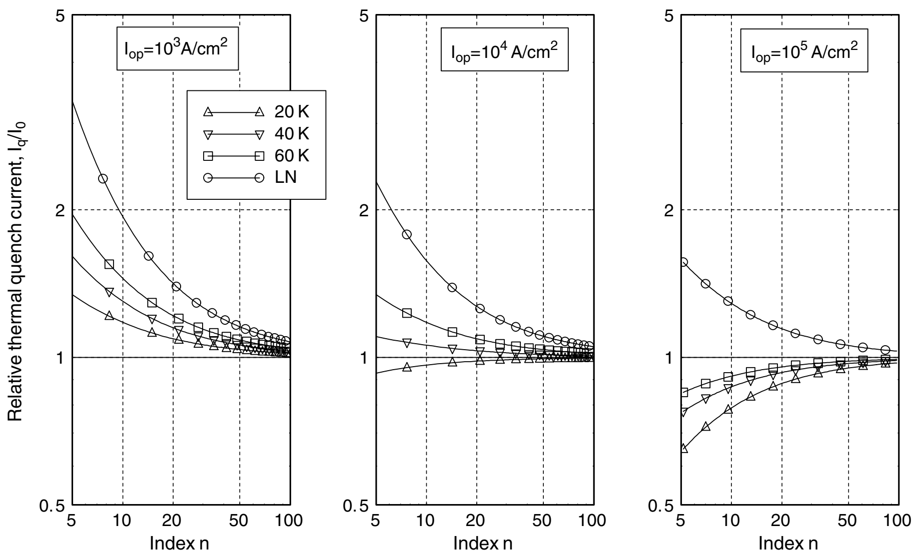

Fig. 4. Relative thermal quench current vs. n for different current densities (9). Cooling and other parameters are taken from the experiments [4,13].

similar to LTS devices. So, low n may be somehow advantageous. This conclusion could be important for Nb_3Sn based large CICC where reduction of index n was observed [21]. In spite of rise of current sharing temperature due to low n, large CICC may be quite stable even at transport currents much closer to its critical current. In principle the analysis [3] and formulas (8)–(12) could be used for large CICC cables also [27]. In this case it is necessary to take into consideration the variation of both, helium and conductor temperatures.

3.2. Maximum temperature and maximum voltages

Two major differences are in quenches of LTS and HTS devices. Due to locality temperature rise in LTS is quick from the very beginning of a quench. On the other hand, in HTS devices due to quasi-uniformity of heating quench develops in two stages. There is rather slow temperature (and voltage) rise until time t_q and temperature T_q (voltage E_q). Then, very fast, tangential rise starts, like in LTS superconductors. If a quench could be detected before t_q, the protection measures could be performed before a device jumps to the regime of dangerous temperature rise.

The influence of index n on the quench development process is shown in Fig. 5, where time dependence (8) of the temperature is shown for two index values. One can see that if index rises, quench develops much faster like in LTS devices:

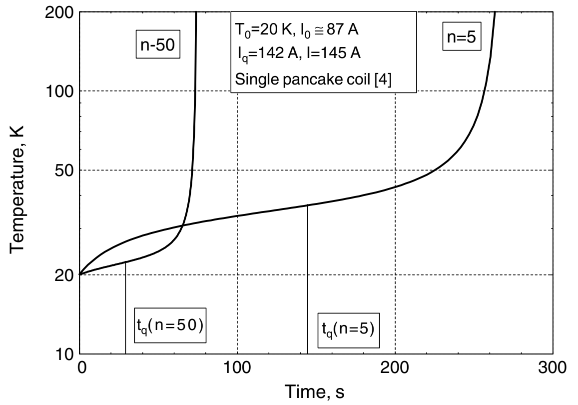

Fig. 5. Temperature vs. time dependence for different index n values. Data are taken from experiments [4].

first, slow stage is not observed. This example was calculated on the base of experimental parameters of single pancake coil [4]. They are indicated in Fig. 5.

The temperature T_q (electric field E_q) may be considered as maximum allowed heating temperature in spite it is rather small. Anyway, immediately after the temperature exceeds it, very fast (and therefore dangerous) temperature–voltage rise starts. This accelerated heating process or thermal instability is a kind of so-called "blow-up" regimes [22]. Such regimes may happen in a nonlinear media if the heat release $Q(T)$ in a media is a sharp function of its temperature T as we have in superconductors (3). At these regimes the temperature can formally turn into infinity during a finite time interval.

One can see that the temperature T_q described by (11) will be close to T_0 if n rises. It means that the thermal instability can occur at lower temperature, like it is in LTS conductors (see Fig. 5). Increasing of n obviously makes quench behavior more similar to LTS conductor.

3.3. Quench time

Quench time is another extremely important parameter in quench analysis that determines time allowed for quench detection and protection system activation delay. In LTS devices is determined by (6) or (7).

For HTS devices, as the characteristic time for a quench could be considered the time determined by (10). It is the time after which very fast temperature/voltage rise starts—thermal instability quickly develops. From (10) one can derive that at high-transport currents $t_q \sim 1/I$. Thermal instability also develops slowly because of high-specific heat. That means much slower quench development than in LTS. Therefore, a quench protection system might have more time to detect a quench and to protect a device.

We may determine the time necessary to reach some maximum temperature from (9). These times for different maximum temperatures are shown in Fig. 6 in dependence on index n for the same case and coil as in Fig. 5 (single pancake coil, transport current 145 A, I_q – 142 A [4]). With the index rise

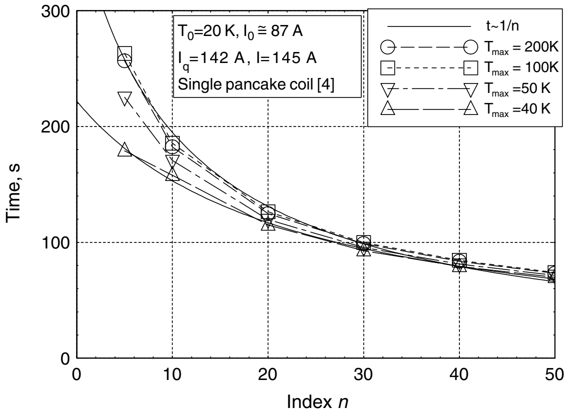

Fig. 6. Time of heating to the temperature T_{max} vs. index n. Parameters are taken from experiments [4].

this time becomes less and closer to each other. They are inversely proportional to index n. The most important note is that even at fast rise stage quench development rate in HTS devices is much slower than in LTS superconductors (seconds instead of milliseconds, see Fig. 6). It is not only a cosequence of low index value, but mainly because of high-specific heat at higher operating temperatures. Major parameter is the specific heating time t_h that is directly proportional to the specific heat. Using (10) one can scale quench time t_q in HTS devices as it is shown in Fig. 7 [8]. One can see that calculated and experimental data agree well.

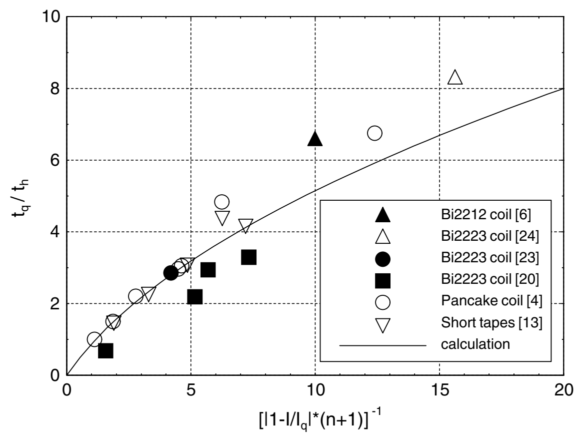

Fig. 7. Dependence of relative characteristic time of quenches on ratio between transport current I and quench current I_q [8]. Symbols: data taken from the literature [4,6,13,20,23,24].

4. Conclusions

We considered the influence of index n and other parameters of quench development of LTS and HTS devices. The major consequence of n-change (as well as specific heat of superconductors) is the change of thermal instability development time. In LTS devices instability develops quickly with quick nucleation of normal zone and further analysis of quench is performed from the consideration of the propagating normal zone. In HTS devices thermal instability develops slowly and it is more convenient and practical to consider thermal quench development without consideration of normal zone propagation. Two stages of quench development are present in HTS devices with change of velocity of temperature/voltage rise. The quench in LTS devices is fast and local process; the quench in HTS devices is slow and quasi-uniform process.

All this lead to the following:

- Change of the superconducting devices design criteria from LTS “critical current design criterion” to HTS “thermal quench design criterion”.
- Change of criteria of allowable heating temperature during quench: LTS is maximum heating temperature T_{max}, HTS is the temperature T_q, when the slope of the dependence $T(t)$ is drastically changing.
- Change of the quench time criteria: LTS is time necessary to heat a device up to T_{max}; HTS is time t_q, time till the change of the slope of $T(t)$ curve.

The theory of thermal quench in HTS superconducting devices is well developed and verified by experiments. In principle, this theory may be used for LTS superconductors with low n-value like NbSn based large CICC.

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