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Variation of Quench Propagation Velocities in YBCO Cables

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Abstract We show by modelling that the quench propagation velocity is not constant in HTS coils but it changes during the quench. Due to the large temperature margin between the operation and the current sharing temperatures, the normal zone does not propagate with the temperature front. This means that the temperature will rise in a considerably larger volume when compared to the quenched volume. Thus, the evolution of the temperature distribution below current sharing temperature T_{cs} after the quench onset affects the normal zone propagation velocity in HTS more than in LTS coils. This can be seen as an acceleration of the quench propagation velocities while the quench evolves when margin to T_{cs} is high. In this paper we scrutinize quench propagation in a stack of YBCO cables with an in-house finite element method software which solves the heat diffusion equation. We compute the longitudinal and transverse normal zone propagation velocities at various distances from the hot spot to demonstrate the distance-variation of these velocities. According to the results in our particular simulation case, the longitudinal normal zone propagation velocity is 30 % higher far away from the quench origin compared to its immediate vicinity when $T_{op}=4.2$ K and $T_{cs}=15$ K.

Keywords high temperature superconductors · normal zone propagation · quench simulation · stability analysis · superconducting magnets

1 Introduction

The quench dynamics of low temperature superconductors (LTS) have been extensively studied and docu-

mented [1]. High temperature superconductors (HTS) have also been widely studied after their discovery, however, the quench dynamics of HTS are still not completely understood [2–6]. Especially the large difference in normal zone propagation velocity (NZPV) between LTS and HTS magnets [7–9] and the large variation in the temperature margin (difference between current sharing and operation temperatures) in HTS magnets provide completely different environments for a quench development.

It has been proposed that NZPV is constant in HTS magnets as it is in LTS magnets [7]. This result allows one possible modelling method for HTS magnets in a coil domain: add isothermal shells on top of each other according to the NZPV. This method was initially proposed by Wilson for the quench simulations of NbTi magnets [1] and later developed by, e.g., Rossi and Sorbi [10]. Naturally, when modelling quench evolution in superconducting magnets using NZPV based methods, knowing NZPV with enough accuracy in longitudinal and transverse directions is crucial. The methods to gather NZPV data are either experimental [8, 9, 11] or computational [12–17].

In this paper we simulate a quench in a stack of cables having insulation in between and compute the normal zone propagation velocities from the results. We focus on possible issues that can be faced during experiments. In section II we describe our computational tool and the underlying equations as well as the modelling domain we used. In section III results from NZPV computation are presented and discussed. Both the longitudinal and transverse NZPV are considered.

2 Computational Model

In this section we present the equations that our finite element method based simulation tool solves in the quench simulation. Additionally, the modelling domain that was used in the simulations is presented in detail. Also, we present how we determined NZPVs from the simulation data in the post-processing phase.

2.1 Quench modelling procedure

We solve the heat diffusion equation, which can be presented as

$$\star(d\lambda \star dT + Q) = C\partial_t T, \quad (1)$$

where d is the exterior derivative [18, Ch.14], $\star$ is the Hodge star operator [18, p.73], λ is the thermal conductivity, T the temperature, Q the volumetric heat generation and C the volumetric heat capacity.

Volumetric heat generation, namely Joule heat generation, was computed using

$$Q = \rho \|J\|^2, \quad (2)$$

where ρ is the effective resistivity of the cable consisting of a superconductor and the metal matrix in parallel. Superconductor resistivity was computed with the power law [6, 19]

$$\rho(B, T, J) = E_c \frac{\|J\|^{n(B, T)-1}}{J_c(B, T)^{n(B, T)}}, \quad (3)$$

where E_c is the electric field criterion, J_c the critical current density of the superconductor and n the index number of the superconductor.

2.2 Modelling domain used in NZPV computation

The cable configuration involved is shown in Fig. 1 (a). It consists of two YBCO tapes soldered together with copper shunt in the middle. This configuration was motivated by the HTS insert magnet study in [20]. Two CuBe_2 tapes have been co-wound to strengthen the cable mechanically and to provide protection in case of a quench. The insulation layers are made of kapton. Relative material proportions of the cable are presented in Table 1. The thickness of the copper layer was $72 \mu\text{m}$ and the individual thicknesses of the two CuBe_2 and insulation layers were $100 \mu\text{m}$ and $30 \mu\text{m}$, respectively. In addition, the thicknesses of the two YBCO tapes consisting of YBCO, buffer layers and the hastelloy substrate, were $64 \mu\text{m}$.

Fig. 1 (a) Cable configuration with insulation layer used in the quench computations. (b) Schematic view from the part of the computational domain used in the simulation. Homogenized material parameters were used for the cable sections [5]. Only the insulation of the cable was modelled as an insulation layer. Figures are not in scale. In (b) not all the modelled cables are shown.

Table 1 Relative material proportions of the non-insulated cable

Copper	18 %
CuBe_2	50 %
Hastelloy+YBCO	32 %

The modelling domain is presented in Fig. 1 (b). It is the straight part from the coil used in our previous work [21], but elongated in order to remove the end effects from the study. The modelling domain consists of 35 cable turns, each consisting of a cable presented in Fig. 1 (a), with insulation layer between each turn. The quench origin, having the length of 5 mm, is located in the middle of the stack in the 18th cable. The stack length was 640 mm. Discrete symmetry was utilized and only half of this was modelled [22]. In addition, adiabatic boundary conditions were applied to the modelling domain.

Black dots in Fig. 1 (b) present the points in which the propagation of the quench frontier was monitored for post-processing purposes. Each point was considered as a quenched point when its temperature rose above the current sharing temperature (T_{cs}). For the longitudinal quench propagation, we used points in the same cable with the hot spot. For the transverse propagation, we used one point in each cable. Points in Fig. 1 (b) do not indicate the real number of points used in the computation but are merely for visualization of the modelling setup. To be specific, we had points in the cable including the hot spot in the longitudinal direction every 10 mm. In the transverse direction, the points were at the center of every cable, thus the distance between the points was 0.46 mm .

2.3 Operation Conditions

The material parameters for thermal conductivity and volumetric specific heat were taken the same as in our previous work, presented in [21]. Values used for the matrix resistivity were presented in [21]. In this case we used constant value of 20 for n , though. J_c was computed as in our previous work [21].

Magnetic field was set to a constant in a way that a certain, uniform, current sharing temperature (T_{cs}) was achieved over the whole modelling domain. Here, the T_{cs} is defined as the temperature where the critical current is reached with given magnetic flux density. This way we could study the temperature margin influence on the normal zone propagation velocity and leave other aspects out to determine the corresponding T_{cs} . T_{cs} of 15 K is common in high field HTS magnet designs operating at LHe in a large fraction of the windings [23], though the lowest temperature margin could be similar to LTS magnets. The parallel and perpendicular field values and corresponding values of T_{cs} used in the computations are presented in Table 2. The field values are

Table 2 Magnetic field values used in the computation

Parallel [T]	Perpendicular [T]	T_{cs} [K]
15.0	2.0	15.2
17.0	2.5	10.0
15.5	3.0	5.0

only used to achieve the corresponding T_{cs} values and are not taken from any existing magnet design.

The operation temperature in the simulations was 4.2 K and the nominal operation current was set to 2800 A as in [20], which corresponds to the engineering current density J_e of 250 A/mm². A quench was initiated by setting the critical current to 0 A at the hot spot in Fig. 1 (b) as in our previous work [21], [24]. By doing this we can create much smoother quench procedure compared to triggering the quench with a short heat pulse [25].

2.4 Computation of NZPVs

The quench simulation was followed by the NZPV computation analysis. We analyzed when certain points within the magnet shift from superconducting state to the normal state. The transition is not sharp due to the power-law but we utilized T_{cs} for the definition of the crossover point.

During the simulation, we saved temperature of every point k (those shown in Fig. 1 (b)) at every time

step i . Then, we collected those time instants t_q^k at which each point shifted above T_{cs} by finding t_q^k such that

$$\forall i < q \quad T(t_i^k) < T_{cs} \quad (4)$$

$$\text{and} \quad T(t_q^k) \geq T_{cs} \quad (5)$$

hold. In other words t_q^k is the time where the temperature of the point k rose above current sharing temperature.

NZPV between points k and $k + 1$ was computed with

$$\text{NZPV} = \frac{\Delta}{t_q^{k+1} - t_q^k}, \quad (6)$$

where Δ is the distance between the points i.e. Δz and Δx for the longitudinal and transverse propagation, respectively.

3 Results and Discussion

Shown and discussed here, albeit separately, are the longitudinal and transverse propagation velocities. Also, we propose some guidelines for performing NZPV measurements at low temperatures for HTS with relatively large temperature margins.

3.1 Longitudinal Propagation

The simulated normal zone longitudinal propagation velocities are presented in Fig. 2. NZPV is not constant

Fig. 2 Longitudinal NZPV as a function of distance from the hot spot with different values of T_{cs} . Plot is normalized to a NZPV value achieved from the distance of 100 mm from the hot spot. The inset presents absolute values.

near the hotspot but increases or decreases considerably depending on T_{cs} . However, the early behaviour may depend on a way to initiate the quench. With T_{cs} of 15 K, the NZPV levelled off to a 30% higher value than the one recorded 25 mm away from the hot spot. The lower NZPV near the hotspot is the result of higher T_{cs} when the heat from the hotspot diffused further into the magnet without extending the quenching volume immediately.

As the quench evolved, a higher percentage of the domain volume turned out to be between the initial temperature and T_{cs} . Thus, the normal zone propagated faster than in the beginning of quench process. This behaviour is illustrated in Fig. 3. Small plateaus on the curves are due to the temperature rise above 4.3 K in the whole coil. When the T_{cs} value was taken equal to 5 K, the whole modeling domain became normal in about 0.25 s. After the T_{cs} -value was doubled to become 10 K the whole domain reached the temperature of 4.3 K about 0.1 s later than in the case where the T_{cs} was 5 K. The simulation was terminated when the hot spot temperature reached 400 K. When T_{cs} was 5 K, whole modelling domain was normal. However, when T_{cs} was 10 K or 15 K only 80% or 40%, respectively, was normalized. Thus, the large temperature gradients are present when the HTS materials are used.

Fig. 3 Volumetric fraction of the volume that has reached T_{cs} and volume where $T \geq 4.3$ K. This means temperature increase of more than 0.1 K.

The change in NZPV levelled off about 100 mm distance from the hotspot in this modelling case. This is a result from global temperature increase during the quench. Further modelling is required to study if there is some correlation between T_{cs} , temperature increase

and the distance where NZPV evens out. However, we can derive a conclusion, that when measuring NZPV in a longitudinal direction, there is certain distance from the hotspot where the voltage taps should be attached to get reliable measurement data of NZPV over the whole coil volume. For example using simulation data with $T_{cs}=15$ K, we fitted a curve

$$\text{NZPV}(x) = 0.4237 - 0.2399 \cdot \exp(-0.037 \cdot x), \quad (7)$$

where x is the distance from the hotspot. According to the fit (7) NZPV is 98.6 % of its maximum value of 0.4237 m/s at the distance of 100 mm from the hotspot. The fit for NZPV is presented in the inset of Fig. 2 to illustrate the correspondence with the computation.

With T_{cs} of 5 K, NZPV decreased very rapidly at first. This is due to the rapid quench in the immediate vicinity of the hotspot due to its high heat generation. The hotspot was in the beginning of the simulation completely in the normal state. Note that, the hot spot does not obey current sharing model, unlike the rest of the coil. When the quench frontier propagated onward from the hotspot, points in the modelling domain shift first to the current sharing state when the superconducting material was still partly superconducting. Thus, the heat generation was not as high as in the region completely in the normal conducting state, slowing down the normal zone propagation.

Fig. 4 presents temperature distributions along one cable at different time instants when T_{cs} is 15 K. It can be seen that the quench propagates 15 mm between 50 ms and 100 ms and 22 mm between 350 ms and 400 ms. Thus, NZPV increased more than 30 % during the quench as also shown in Fig. 2.

Fig. 4 Temperature as a function of distance from the hot spot when T_{cs} is 15 K (dotted line in figure). First curve is at 1 ms, second at 50 ms, third at 100 ms and so on. Quench evolution distance on a 50 ms time frame: a) 15 mm b) 20 mm c) 21 mm d) 22 mm

3.2 Transverse Propagation

The transverse NZPV results are presented in Fig. 5. A normal zone propagated a substantially shorter dis-

Fig. 5 Transverse NZPV as a function of distance from the hot spot with different values of T_{cs} . Plot is normalized to a NZPV value achieved from the distance of 3 mm from the hot spot. Inset shows absolute values.

tance in the transverse direction than in the longitudinal one. This was due to the considerably lower thermal conductivity of the insulation compared to that of the HTS cable. When the simulation was terminated, the normal zone had propagated to the edge of our modelling domain in the transverse direction in every simulation case, which was about 8 mm from the hotspot (i.e. 17 cables).

According to Fig. 5 the quench evolved in a similar way in both the transverse and longitudinal directions. The rapid NZPV increase at a 8 mm distance from the hot spot in Fig. 5 seems to result from the closely-pitched adiabatic boundary of the modeling domain. Thus, further modeling and measurements are required to analyze the longitudinal and transverse normal zone propagation at various values of T_{cs} as a function of the distance from the hot spot. The NZPV measurements will be performed on the future YBCO insert magnet to be supported by appropriate simulations.

The temperature profiles in transverse direction were investigated in Fig. 6 in the same way as in Fig. 4. With current sharing temperature of 15 K, the normal zone propagated 0.8 mm between 50 ms and 100 ms and 1.0 mm between 350 ms and 400 ms. Thus, the absolute value of NZPV was much lower than that in the longitudinal direction, however, the velocity increased by 25% in the course of quench. At the same time, some

plateaus occurred before the quenched volume ranged up to the cables located near the domain boundary. The corresponding NZPV values are 10 mm/s, 3 mm/s and 2 mm/s for T_{cs} values of 5 K, 10 K and 15 K, respectively.

Fig. 6 Temperature as a function of distance from the hot spot when T_{cs} is 15 K (dotted line in figure). Time between the curves is constant 50 ms. Quench evolution distance on a 50 ms time frame: a) 0.8 mm b) 0.9 mm c) 0.9 mm d) 1.0 mm

4 Conclusions

We simulated a quench occurred at the operation temperature of 4.2 K in a stack of YBCO cables by solving the heat diffusion equation with finite element method. In particular the normal zone propagation velocities in the transverse and longitudinal directions were analyzed. Various values of T_{cs} were used to analyze the difference in NZPV corresponding to different temperature margins in an actual magnet.

A normal zone propagation in longitudinal direction varied as much as 30% until it levelled off. Transverse normal zone propagation is slow, in the region of 0.1 cm/s depending on the T_{cs} , when insulation layers between cables are present. Due to such a slow NZPV the levelling off of the NZPV that was seen in the longitudinal direction was not observed in the transverse direction even when 400 K temperature in the hotspot was reached and the simulation was terminated.

By these simulations, we showed that the normal zone propagation velocity is not constant during a quench but it depends on the evolution of the temperature distribution. After a certain threshold distance in the longitudinal direction, NZPV levels off. Thus, studying the placement of voltage taps is crucial for reliable NZPV measurements. NZPV should be measured at sufficient distance from the hotspot to get reliable measurement results.

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