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Modelling of Minimum Energy Required to Quench an HTS Magnet with a Strip Heater

E. Härö, A. Stenvall, J. van Nugteren and G. Kirby

Abstract—Due to the wide spectrum of current sharing temperatures in an HTS magnet, estimating the energy required to quench the magnet is a complicated task. On the other hand, quenching an LTS magnet for quench characterization purposes with a heater is straight-forward due to the small temperature margin, and correspondingly low minimum quench energy (MQE). To estimate the required energy for LTS magnet, the analytic concept of MQE can be utilized. In this paper we propose that only numerical simulations can give adequate estimates to the MQE of an HTS magnet for measurement purposes. Further, due to the high enthalpy margin, the utilization of spot heaters with short energy pulses becomes questionable. We present in detail the effect of heater's pulse length to the MQE when a strip heater is utilized for quenching. In addition, the effect of the heater area on MQE is studied. We consider the model of a REBCO coil to be constructed and tested in a European project EuCARD-2. According to the results: 1) MQE increases almost linearly for pulse lengths between 100 ms and 500 ms. 2) When the heater area is enlarged, the required energy per area saturates to a certain value related to the coil's enthalpy margin. 3) MQE obtained with a traditional analytic approach based on a minimum propagating zone (MPZ) underestimates considerably the numerically obtained MQE.

Index Terms—high temperature superconductors, minimum quench energy, quench simulation, stability analysis, superconducting magnets

I. INTRODUCTION

THE large hadron collider (LHC) is reaching its maximum beam energy using conventional low temperature superconductor technology (LTS) [1]. Next step to be taken in the research area of superconducting accelerator magnets is the High Luminosity LHC (HL-LHC) [2], which utilizes Nb₃Sn magnet technology to reach 16 T fields [1], [3]. To reach fields beyond 16 T, high temperature superconductor HTS technology has to be exploited for an upgrade to 20 T, which is a possibility in the high energy upgrade of LHC (HE-LHC) [1], [4]. Within the two European projects, EuCARD and EuCARD-2 [4], [5], the new generation HTS accelerator magnets are studied.

For HTS magnets operating at low temperatures with high operation currents, only limited amount of quench detection measurement information is available. Due to this, within the

EuCARD-2 project several small HTS coils, namely Feather-M0, will be constructed for quench detection and protection measurement purposes [6]. The EuCARD-2 project aims for the development of an HTS magnet Feather-M2 (produces 5 T) [7], which will be constructed after the initial tests are concluded using the small test coils. HTS magnets have a high margin for quench when operating at low temperatures, thus, estimating sufficient heater energies to quench the magnet without causing permanent damage either to the heater or to the coil is invaluable.

Wilson presented the concept of minimum quench energy (MQE) [8] to estimate the energy that is required to quench an LTS magnet. Wilson defined the smallest normal conducting volume that is required in the coil for the normal zone to spread, namely minimum propagating zone (MPZ). The energy that is required to create MPZ is called MQE. By using the MQE concept the heater energy required to quench an LTS magnet for measurement purposes can easily be estimated.

In fact, the first widely used computer program for simulating quench was Wilson's QUENCH [8], which is based on the MPZ concept. QUENCH was invaluable tool in the 1980s when computers were not advanced enough to solve large problems in three dimensions utilizing finite element method (FEM) or finite difference method in adequate time. Later, other codes based on quench propagation were also presented, e.g. PQUNCH [9] and QLASA [10]. In the 1990s, an extensive code based on difference method was developed at the National High Magnetic Field Laboratory [11], [12]. Later, commercial software solving heat diffusion equation with FEM have been utilized too. For example, ANSYS [13] was used to simulate quench in Nb₃Sn magnets [14]. Recently, also Comsol [15] has been utilized in quench simulations [16] and Opera has developed a tailored module for quench simulation [17]. In addition, simulation tools for specific duties have been developed. For example, CUDI has been used to analyze quench propagation in Rutherford cables [18].

A large temperature margin between the operation temperature and the current sharing temperature (T_{cs}) is common for HTS magnets operating in liquid helium [19], [20]. Due to the high T_{cs} , the quench frontier does not propagate with the temperature frontier in HTS magnets [20]. Therefore, codes based on the normal zone propagation velocity are not adequate when simulating quench in HTS magnets. Thus, we show that the MQE concept relying on analytical formula is not feasible when devising the range for the operation of quench onset heaters in HTS magnets. We propose that the MQE could be only investigated numerically with reasonable

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accuracy for HTS magnets that are to be quenched with a strip heater for quench measurements purposes. To avoid confusion, in this paper we use the term minimum energy required to quench (MERQ) to express the MQE obtained using numerical computation.

In this paper we study the difference of analytical and numerical MQE for HTS insert magnet. MERQ is determined in one particular case and the effect of heater pulse length as well as the heater area to MERQ is studied in detail. In section II we present the computational model, modelling domain and operation conditions used in this work. In section III we present the results for MQE and MERQ computations for the REBCO research magnet, Feather-M0. In the end the conclusions and the feasibility of MQE concept in HTS magnets is discussed.

II. COMPUTATIONAL MODEL

In this section we present the equations our FEM software solves for. In addition, the computation method for MQE is presented as well as the operation conditions and the modelling domain used in this work.

A. FEM simulation

FEM simulations were performed with our in-house software built on top of the open-source mesh generator software GMSH [21]. Our software solves for the heat diffusion equation

$$\nabla \cdot \lambda(T) \nabla T + Q(T, \mathbf{B}) = C(T) \frac{\partial T}{\partial t}, \quad (1)$$

where λ is the anisotropic thermal conductivity, T is the temperature, Q is the volumetric heat generation, $\mathbf{B}$ is the magnetic flux density and is C the volumetric heat capacity.

Joule heat generation within the modelling domain was computed using

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

where ρ is the effective resistivity of the cable and J is the current density of the cable. Effective resistivity can be computed by assuming the materials of the cable being in parallel as shown in [22]

$$\frac{1}{\rho_{eff}(T)} = \sum_{i=1}^n \frac{f_i}{\rho_i(T)}, \quad (3)$$

where f_i is volumetric fraction of the material i and $\rho_i(T)$ resistivity of the material i . Superconductor resistivity was computed with the power law [23], [24]

$$\rho(B, T, J) = E_c \frac{\|J\|^{n(B, T)-1}}{J_c(B, T)^{n(B, T)}}, \quad (4)$$

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 characterizing the steepness of the resistive transition.

The strip heater was modelled as a Neumann boundary condition, e.g. the heater had no volume but an area on the coil surface and there was a heat flux through the boundary to the coil. Naturally, this does not represent the energy required

to be inserted in a particular heater. However, our aim was to abstract out the heater, especially its contact to the coolant, and only study the internal behaviour of the coil. This also allowed us to compare the simulation results to the MQE. The heater energy Q_h was computed using

$$Q_h = P_h t_h, \quad (5)$$

where P_h is the heater power and t_h is the time that the heater was active. The heater energy was evenly distributed over the whole surface of the heater. Rest of the boundary of the modelling domain, i.e. excluding the heater connection, was bounded by adiabatic boundary condition.

B. Computation of MQE

MPZ is the smallest normal conducting volume in the coil that causes a propagating normal zone that eventually leads to a quench [8]. MQE is the energy that is required to create the MPZ. Conceptual figure of the MPZ ellipsoid is presented in Fig. 1.

Fig. 1. Normal zone ellipsoid.

The major radius R_{mz3} is computed, according to [22], as

$$R_{mz3} = \sqrt{\frac{3\lambda_l (T_{cs}(B, J_{op}) - T_{op})}{\rho_m J_m^2}}, \quad (6)$$

where λ_l , T_{cs} , J_{op} , T_{op} , ρ_m and J_m are the thermal conductivity along the cable, the operation sharing temperature, the operation current density, the operation temperature, the resistivity of the matrix metal and the current density in the matrix metal after the transition the the normal state, respectively.

Due to the anisotropic thermal conductivity within the cable the radii R_{mz1} and R_{mz2} in the MPZ ellipsoid are not identical to the R_{mz3} . According to [8] we can estimate the radii with

$$R_{mzi} = \sqrt{\frac{\lambda_i}{\lambda_l}} R_{mz3}, \quad (7)$$

where λ_i is the thermal conductivity at the direction of the x_i -axis.

When the volume of the MPZ ellipsoid, V_{MPZ} , is known, we can compute the MQE with

$$MQE = V_{MPZ} \int_{T_{op}}^{T_{cs}(B, J_{op})} C(T) dT \quad (8)$$

C. Modelling domain and operation conditions

The modelling domain used in this paper is presented in Fig. 2. The coil is the same almost racetrack-shaped, namely Feather-M0 [7], [25], that was used in our previous work [19] with the addition of the heater at the coil inner radius at the middle of the straight part of the coil. The coil consists of 5 turns of 1 mm thick and 12 mm wide Roebel cable manufactured from 15 REBCO tapes each having width of 12 mm before the punching [26].

Fig. 2. Modelling domain for our simulations. Heater is located on the coil inner radius in the middle of the straight part. In this figure the heater length was 31 mm.

The relative material proportions of the insulated coil are presented in Table I. Homogenized material properties were used for the whole modelling domain. Effective material properties were computed according to the [22] and Cryocomp [27] was used as the material library, except for the copper resistivity, which was taken from [28]. RRR-value of 100 was used for copper.

TABLE I
RELATIVE MATERIAL PROPORTIONS OF COIL UNIT CELL

Copper	31.5 %
Hastelloy + REBCO	38.5 %
G-10	30 %

The location of the heater was selected in a way, that it would only heat up the innermost turn of the coil. In addition, the location was selected in a way that it will be in an area where the T_{cs} will vary within the heater area. In this particular case the T_{cs} was between 36-58 K below the heater.

Operation conditions for the coil are presented in Table II. Operation temperature of 4.2 K and operation current of 6 kA were used [25]. The magnetic flux density within the coil area was computed using Field [29], while the maximum magnetic field in the magnet area was 1.5 T. Roebel cable critical current as a function of temperature, magnetic flux density and angle was computed according to the [30]. Even though the superconductor n -value is a function of magnetic flux density and temperature, for simplification a constant value of 20 was used in this work due to the lack of better data.

III. RESULTS AND DISCUSSION

In this section we present the results from numerical MERQ analysis and compare the results to the MQE computation

TABLE II
OPERATION CONDITIONS

Parameter	Value
Initial Current	6 kA
Initial Temperature	4.2 K
Cable Area (insulated)	12.2 mm ²
Copper RRR-value	100
Superconductor n -value	20

for the given magnet. In addition, we study the effect of strip heater pulse length and heater area to the MERQ. In the end we discuss about the feasibility of the Wilson's analytical approach to compute MQE for HTS magnets. As a reference case we selected the heater to have an area of 130 mm² (18 mm long and 7.2 mm wide) and the length of the heater pulse was 25 ms. Later, parametric analyses were scrutinized to observe the effect of heater area and pulse length on MERQ. Within these parametric analyses when heater area or pulse length was varied, the other variable was kept constant with the same value as in the reference case.

A. MERQ vs. MQE: reference case

Fig. 3 presents the hot spot temperatures as a function of heater energy at different time instances after the heater ignition. After 25 ms, i.e. the time instant when the heater was turned off, the hotspot temperature was from 65 K to 198 K when the heater energy was from 1 J to 4 J, respectively. However, if the heater energy was below 1.55 J, the magnet did not quench and the hotspot temperature kept decreasing when time elapsed. When the heater energy was above 1.55 J the hotspot temperature increased after the heater was switched off and the magnet quenched. Thus, increasing the hotspot temperature to even 65 K from the operation temperature of 4.2 K with 1 J was not sufficient to quench the magnet in this case. MERQ for this case was 1.55 J which corresponded to the 95 K hotspot temperature at the time when the heater was switched off.

Computing the MQE with the analytical formula in this case resulted in the MQE of 50 mJ and 150 mJ with T_{cs} of 36 K and 58 K, respectively. With the minimum T_{cs} of the magnet, 36 K, the MQE was 30 times smaller than the MERQ and using the maximum T_{cs} , 58 K, the MQE was 10 times smaller than the MERQ. The MQE underestimates the MERQ significantly, thus, it is not recommended to use MQE to estimate strip heater energy required to quench an HTS coil.

B. Parametric analyses

Fig. 4 presents MERQ as a function of heater pulse length. MERQ varied between 0.8 J and 7 J with pulse lengths varying from 5 ms to 500 ms, respectively. With short heater pulse lengths, MERQ increased rapidly, however from 100 ms to 500 ms MERQ increased almost linearly. HTS magnet quench measurements may require long heater pulses due to the temperature rise within the heater, which was not a subject of study in this work. Long heater pulses translate into long simulations, which might be problematic when

Fig. 3. Hot spot temperature at different time instances after the heater ignition. Heater is switched off after 25 ms.

using numerical simulations. In these cases the possibility to approximate the increase of MERQ linearly is a feasible solution. Fig. 4 shows that for the measurement purposes short pulses are difficult from the power supply point of view due to the larger power, and thus, higher temperatures within the heater volume. For example, 16.7 W, 20 W and 40 W heater power was required with pulse lengths of 300 ms, 200 ms and 50 ms, respectively.

Fig. 4. MERQ as a function of heater pulse length.

In this second parametric analysis we studied the influence of heater's cross-section area on MERQ. Fig. 5 presents the MERQ and MERQ relative to the heater's cross-sectional area as a function of heater area. The MERQ increased from 1.2 J to 2.2 J with heater area varying from 22 mm² to 300 mm² (by lengthening the heater from 3 mm to 31 mm). The MERQ increases almost linearly as a function of heater area, however,

the MERQ divided by heater area saturates towards a certain value, 8 mJ/mm². Surprisingly, this saturation value corresponds the enthalpy margin, from 4.2 K to the average of T_{cs} , 47 K, of a single Roebel cable. Fig. 5 shows that smaller heater area means smaller MERQ, however, the hotspot becomes more localized. Hotspot temperature rises more rapidly in the small hotspot, thus, burning the coil is a larger threat due to the difficult quench detection. Furthermore, it is possible to burn the heater due to the large power density within a small volume [31], thus, avoiding spot heaters when quenching the coil is advisable.

Fig. 5. Solid line and dashed line present MERQ and MERQ divided by heater area as a function of heater area, respectively.

IV. CONCLUSIONS

A numerical approach was taken to estimate the minimum quench energy of an HTS coil for quench initiation purposes. We showed that Wilson's analytical approach underestimates considerably the MQE, due to the high temperature margin of HTS magnets. Further, numerical modelling gives more insight to the quench onset heater design, because the effect of the heater contact area and pulse length can be considered. Consequently, when preparing for quench detection and protection measurements for HTS magnets, numerical approach to design the strip heater for quench ignition is preferred. We denoted the numerically modelled MQE as MERQ (minimum energy required to quench).

The MERQ was numerically computed for an HTS reasearch magnet, Feather-M0, with a reference heater area (130 mm²) and powering pulse length (25 ms). With operation temperature of 4.2 K and operation current of 6 kA the MERQ was 1.55 J, which was 10-30 times larger than the result given by analytical MQE concept. The MQE was computed with two different values of T_{cs} , 36 K and 58 K, which represent the range for T_{cs} below the heater.

In the parametric analysis we studied the effect of heater pulse length and heater area to the MERQ was also under consideration. The MERQ increased almost linearly as a function of heater pulse length from 0.8 J and 7 J with pulse lengths varying from 5 ms to 500 ms, respectively. Finally, the MERQ increased linearly as a function of heater area from 1.2 J to 2.2 J with heater areas varying from 22 mm² to 300 mm².

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