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Hot Spot Temperature in an HTS Coil: Simulations with MIITs and Finite Element Method

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

Abstract—MIITs, a zero-dimensional concept to study hot spot temperature, has been previously used to estimate hot spot temperatures and quench heater delays in NbTi and Nb₃Sn magnets. However, quench behaviour is completely different in high temperature superconducting (HTS) magnets due to the slow normal zone propagation velocity and high temperature margin. Because MIITs concept does not take into account thermal diffusion in the magnet, opposite to the finite element method (FEM) analysis, the difference of these concepts is studied in this paper. Here we have taken the approach to compute the hot spot temperatures for a future HTS magnet, designed to be built from REBCO Roebel cable, with MIITs and FEM simulations. The magnet protection is accomplished with a dump resistor, and the effect of quench detection threshold voltage on the hot spot temperature has been studied. Furthermore, the inductance of the magnet increases with the magnet length. Thus, there exists a maximum inductance of the magnet which should not be exceeded to be able to protect the magnet only with a dump resistor. The hot spot temperatures with different values of inductance are also studied in this paper. Our simulations show, that the hot spot temperatures computed with MIITs are from 60 K to 150 K higher than those of FEM analysis. Thus, MIITs concept seems unreliable when considering hot spot temperatures in HTS magnets protected with only dump resistors. However, MIITs concept might be a usable tool when comparing different magnet designs. If 400 K is the upper limit for the hot spot temperature and the protection scheme includes only a dump resistor, the length of the investigated magnet can be increased to only such value that the magnet inductance is at most 50 mH.

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

I. INTRODUCTION

THE accelerator magnets proposed for the future machines at the 20 T regime require high temperature superconductor (HTS) magnets to be inserted in low temperature superconductor (LTS) outsert magnets. This magnet concept has been considered in the High Energy LHC (HE-LHC) design study [1] and as an option for the Future Circular Collider (FCC), a circular post-LHC accelerator to be constructed at CERN in a long term [2].

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Quench considerations play important role already in these conceptual designs. The quench dynamics of LTS accelerator magnets are well known and documented [3]–[7]. However, the ongoing work with quench protection on HTS magnets still presents serious challenges [8]–[10]. Correspondingly, one important field of study in accelerator magnet R&D is the protection analysis of HTS magnets: first, how to perform it reliably and then the analysis of particular designs.

A zero-dimensional concept to study hot spot temperature was first introduced in [11], and later presented by others [12]–[14]. In this concept, known as MIITs, it is assumed, that during a quench the heat generated in the matrix metal of the superconductor is fully absorbed by the specific heat of the conductor and insulation. Thus, decaying operation current of the magnet increases the temperature of a particular point for a certain period of time. One can estimate the final temperature, corresponding to a given current decay integral, in the hot spot.

Quench simulations performed with the finite element method (FEM) for complicated magnet geometries are challenging and time consuming. Magnet geometry is not taken into account when computing MIITs, thus, MIITs concept has been used for many conceptual protection studies for LTS accelerator magnets [3], [5], [9]. This concept is especially useful, when large fraction of the magnet is quenched with quench protection heaters and the heat conduction in the magnet has limited effect on the hot spot temperature. MIITs computation can be used to study the increase of the hot spot temperature, however, using this method the thermal conductivity in the magnet is neglected. Thus, the slow normal zone propagation velocity of HTS magnets [15]–[17] should be considered to see its effect on the hot spot temperature compared to MIITs computation. Especially if protection heaters, or other method causing rapidly large quenched volume, are not used in the protection scheme.

In HTS coils, the large temperature increase may be very localized [18], [19]. Consequently localized high temperature gradients may exist, which lead to high tensile stresses inside the coil. Delamination of REBCO tapes under transverse tensile stress may limit the possibilities for REBCO usage in future magnets [20]–[22]. In delamination the buffer layer is sheared from the hastelloy substrate, which decreases the critical current substantially after the quench procedure [23], [24]. Therefore, when designing quench protection for a magnet, estimating the whole temperature distribution is a crucial task. The computation of MIITs and finite element analysis (FEA) present two different approaches to consider maximum temperature in the coils. In addition, in case of a localized

heat generation, FEA also gives important information about temperature distribution for mechanical analysis.

In this paper we study the difference between the assumed hot spot temperature increase using MIITs and FEA. Hot spot temperatures given by MIITs and FEA are computed in a scenario where the magnet is protected only with a dump resistor and quench propagates from the initial hot spot only due to the thermal conductivity of the magnet. In section II we present the computational model and the modelling domain that was used in this work. In section III the hot spot temperature results from FEA and MIITs computation are presented and compared. Also the feasibility of MIITs concept in the investigated HTS magnet studies is discussed. In the end conclusions are presented.

II. COMPUTATIONAL MODEL

In this section we present the equations that our finite element method based simulation tool solves for as well as the method to compute MIITs. Operation conditions and material parameters in our modelling domain are also described in detail.

A. FEM simulation

FEM simulations were performed with our in-house software built on top of the open-source mesh generator software GMSH [25]. 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 the temperature, Q the volumetric heat generation, $\mathbf{B}$ the magnetic field density and C the volumetric heat capacity and t is the time.

Volumetric heat generation within the modelling domain, namely Joule heat generation, 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 [26]

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

where ρ_{eff} is the effective resistivity of the cable, f_i volumetric fraction of the material i and $\rho_i(T)$ resistivity of the material i . Superconductor resistivity was computed with the power law [27], [28]

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

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.

B. Computation of MIITs

Computation of MIITs can be done as described in [14] using

$$\int_0^\infty I^2(t) dt = A^2 \int_{T_0}^{T_{\max}} \frac{C(T)}{\rho(T)} dT = \Gamma(T_{\max}), \quad (5)$$

where T_0 is the initial temperature and $T_{\max}$ is the maximum temperature of the hot spot, t is the time, A is the area of the cable and Γ is the MIITs. If the operating current as a function of time is known, we can compute MIITs from the left hand side integral of (5). Because the material parameters and initial temperature T_0 for the studied magnet are known, we can find the value for $T_{\max}$ which gives the same MIITs from the right hand side integral as we get from the left hand side integral. This value for $T_{\max}$ is the maximum hot spot temperature estimated by MIITs.

The current decay can be expressed, as presented in [29],

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right), \quad (6)$$

where I_0 is the initial operation current and τ is the time constant. If only dump resistance R_d is considered, i.e. magnet's normal zone resistance is neglected, τ is constant and can be expressed as

$$\tau = \frac{L}{R_d}, \quad (7)$$

where L is the inductance of the magnet. Thus, higher value for protection resistance speeds up the current decay. However, the terminal voltage of the coil limits the protection resistance to a certain value

$$R_d < \frac{V_{\max}}{I_0}, \quad (8)$$

where $V_{\max}$ is the maximum applicable terminal voltage of the coil, usually in the order of 1 kV [29]. Combining (5)-(7), we can compute the left hand side integral of (5):

$$\int_0^\infty I^2(t) dt = I_0^2 \int_0^\infty \exp\left(-\frac{2t}{\tau}\right) dt = \frac{L}{R_d} \frac{I_0^2}{2}. \quad (9)$$

Note, this means constant dump resistor and no normal zone resistance. In this work we used the same current decay curve for both FEA and MIITs computation. Thus, we first computed FEM simulations using dump resistor. Then we computed the left hand side integral of (5) with the solved current profile, which means utilizing the current value of every time step and linear interpolation in between. Due to using the same current profile for both computations, we neglect the impact from the variation of currents between the models due to the normal zone resistance existing in FEA. Often, this similar approach is utilized when the maximum hot spot temperature is approximated from measured current decay curve [3], [30].

C. Modelling domain

The investigated modelling domain for FEA is presented in Fig. 1. The coil is named Feather-M0 (FM0), and it is the latest version of an HTS insert for future accelerator magnets in the EuCARD-2 project [8]. The FM0 magnet is designed to have five turns of Roebel cable made from 15 12 mm wide

REBCO tapes. The inner diameter of the magnet is 20 mm, outer diameter is 25 mm and the height is 12.2 mm. The operation current of the magnet is 6000 A, which results in the engineering current density J_e of 491 A/mm².

Fig. 1. Modelling domain used for FEM simulations.

The FM0 magnet is divided into two regions in our model, namely, normal region and the hot spot region. These two regions are identical from the material properties point of view, however, the critical current is considered in a different way in these two regions. For the normal region the critical current is computed from the cable critical current surface, which takes into account the angular dependency of the magnetic field. However, for the hot spot we assign a critical current which is lower than the operation current, thus, effectively quenching the magnet slowly, as in our previous work [31]–[33]. The hot spot region, which is located in the area with the highest magnetic field density, is shown in Fig. 1. Apart from the hot spot region, the coil is considered as normal region. Adiabatic boundary conditions were applied to the modelling domain.

Manufacturing long length REBCO Roebel cables is still a demanding task [34]. However, Roebel cable length required for FM0 is 5 m [35], which is manageable. Fig. 2 presents the dummy cable that is similar to the REBCO based cable which will be manufactured in the future to assemble the FM0 magnet.

Fig. 2. Dummy cable produced from stainless steel imitating the cable that will be used to manufacture the FM0 magnet in the future.

Table I presents the relative material proportions of the coil unit cell. The Roebel cable consists of REBCO, hastelloy substrate and copper stabilizer. In the manufacturing process of Roebel cable the punching process always creates void areas in the cable, which has to be taken into account in material parameters. Fiber-glass epoxy insulation was used in this study, however, other insulation materials are still considered for the actual realization of the FM0 magnet.

TABLE I
RELATIVE MATERIAL PROPORTIONS OF COIL UNIT CELL

Copper	31.5 %
Hastelloy + REBCO	38.5 %
Glass Epoxy Insulation	10 %
Void	20 %

D. Operation Conditions

Operation conditions used in this work are presented in Table II. The same conditions were used for both FEA and MIITs computation. Initial current was 6 kA and initial temperature 4.2 K, as designed for FM0. Magnet was quenched by setting the critical current to 0 A in the hot spot region. The choice of critical current does not affect on the hot spot temperature notably, however, it does affect on the total length of computation as shown in our previous work [31]. Further, this assumption links MIITs and FEM well together. FEM simulation was terminated when the hot spot temperature rose over 400 K or the operation current decayed under 20 A, due to the protection, after which the heat generation is negligible in the magnet. We utilized 400 K as a safety limit, though in practice this may not be the case.

TABLE II
OPERATION CONDITIONS

Parameter	Value
Initial Current	6 kA
Initial Temperature	4.2 K
Cable Area (insulated)	12.2 mm ²
Magnetic Field ()	2.5 T
Inductance (varied)	8.16 μ H - 81.6 mH
Protection Resistance	0.15 Ω
Quench Detection Voltage (varied)	10, 30, 50 mV
Copper RRR-value	100
Superconductor n-value	20

Operation current of 6 kA would result in a magnetic field of 1.5 T in the center of the racetrack, however, in this work we used a constant parallel magnetic field of 2.5 T. By using a constant magnetic field, we achieve a constant critical current outside the hot spot region. By using constant critical current distribution in the modelling domain we neglected variables between the models. MIITs model does not take into account different operation conditions, except for material parameters, in the modelling domain, thus, we wanted to unify the magnetic field conditions also in the FEA.

Protection resistance of 0.15 Ω was selected to achieve a terminal voltage of 900 V, which is less than the usual safety limit of 1 kV, with nominal operation current. We also used different values for quench detection voltages (10 mV, 30 mV and 50 mV). Usually there is noise in the detection system, which brings uncertainty to the quench detection. Thus, we studied how the hot spot temperature is affected by the slower quench detection.

Inductance of the studied magnet was varied during the simulations. The real inductance for FM0 is 8.16 μ H [35], but we increased the inductance from 8.16 μ H up to 15 mH in the simulations. For reference, the inductance of the LHC

dipoles is 98.7 mH [36]. Usually the magnet inductance for accelerator magnets is given by H/m unit, thus, increasing the magnet inductance corresponds to a longer magnet. It is important to acknowledge the maximum length of the magnet, that can be protected with only a dump resistor, which we will demonstrate in this paper.

Homogenized material parameters were used in the modelling domain. Effective heat capacity and thermal conductivity were computed as presented in [26]. Cryocomp [37] was used as a material library for all the material constituents, except for the copper resistivity which was presented in [38]. In this work we used a constant value of 20 for n . J_c was computed according to [39].

III. RESULTS AND DISCUSSION

In this section we present the results of MIITs computation and FEA. First we present hot spot temperature behaviour as a function of time with both simulation methods using a constant quench detection voltage. Then, we study the effect of quench detection voltage on the hot spot temperatures. These results can be used to estimate the length of the magnet which can be protected with only a dump resistor.

A. Hot spot temperatures with FEA and MIITs

Hot spot temperatures as a function of time were studied between MIITs computation and FEA and the results are presented in Fig. 3. In this case a constant quench detection voltage of 10 mV was used but the magnet inductance was varied in Fig. 3 (a)-(e). The effect of thermal conductivity can be seen at the start of the simulation in Fig. 3. Solid line and dashed line presents FEA and MIITs, respectively. Using MIITs, the hot spot temperature rose almost linearly during the simulation, however, this kind of behaviour was not observed with FEA. FEA analysis showed, that the hot spot temperature increased slowly in the beginning because the heat diffused from the original hot spot. When the temperature at the proximity of the hot spot had increased to a certain value, the hot spot temperature started to rise again with almost the same time derivative as with MIITs. Furthermore, the slow ascend of hot spot temperature in the beginning of FEA was due to the high current sharing temperature of HTS magnets. Thus, the heat diffused out of the hot spot but did not quench the area around the hot spot immediately.

Temperature rise in Fig. 3 (a) and (e) stopped abruptly but due to different reasons. In the simulation corresponding to Fig. 3 (a), the current decayed from 6 kA to the simulation termination condition (20 A) in around 0.1 ms ($\frac{L}{R_{d1}} = 0.05$ ms) after the detection threshold voltage of 10 mV was passed. However, in the simulations corresponding to Fig. 3 (e) the high inductance of 81.6 mH resulted in such a slow current decay that the hot spot temperature increased to 400 K before the current decayed to 20 A, thus, terminating the computation. The plateaus in Fig. 3 (b)-(d) were due to the prolonged current decay and simulations were carried on with low current values which resulted in almost negligible heat generation.

The hot spot temperatures with different inductances from MIITs and FEA are presented in Table. III. Temperature

Fig. 3. Hot spot temperature as a function of time with the quench detection voltage of 10 mV. Dashed line presents MIITs computation and solid line FEA results.

differences between MIITs and FEA are from 60 K to 150 K with inductances ranging from 8.16 μ H to 81.6 mH. Therefore, when estimating the hot spot temperature in an HTS magnet protected like this the utilization of MIITs has a lot of uncertainty.

TABLE III
HOT SPOT TEMPERATURES

Inductance	FEA [K]	MIITs [K]
8.16 μ H	100	160
0.816 mH	106	174
8.16 mH	175	264
15 mH	257	377
81.6 mH	400	554

B. Effect of quench detection voltage to hot spot temperatures

We studied the effect of quench detection voltage to the hotspot temperature. The results of FEA and MIITs with quench detection voltages of 30 mV and 50 mV with varying inductance are shown in Table. IV. The temperature differences between FEA and MIITs were from 65 K to 150 K with both quench detection voltages. However, the magnet inductance of 15 mH showed that with quench detection voltage of 30 mV, the hot spot temperature was 282 K but with 50 mV voltage the temperature rose to 400 K before the current decayed. Thus, there was over 100 K difference if the quench was detected with 20 mV higher threshold voltage.

The quench detection is equally crucial part in the magnet protection like the protection scheme to prevent dangerously high hot spot temperatures in the magnet. It is notable however, that the result for MIITs is equal with detection voltages of 30 mV and 50 mV in Table. IV due to the equal result of 400 K with FEA. MIITs were computed with the same time frame as FEA, i.e. terminating FEA when reaching 400 K terminated MIITs computation with the same result with detection voltages of 30 mV and 50 mV.

TABLE IV
HOT SPOT TEMPERATURES

Inductance	FEA [K]		MIITs [K]	
	30 mV	50 mV	30 mV	50 mV
8.16 μ H	114	123	179	190
0.816 mH	121	130	193	200
8.16 mH	194	206	290	306
15 mH	282	400	410	554
81.6 mH	400	400	554	554

Current decay curves with different values of inductance and quench detection voltage are presented in Fig. 4. The same current decay profile was used to compute hot spot temperature with MIITs and FEA. The current decay profile is almost identical with different quench detection voltages, only the length of the constant current before the detection depended on the quench detection time. This means that the normal zone resistance had negligible role in the absorption of the total stored energy. Fig. 4 (a) presents the current decay profile with the inductance of 8.16 μ H, where the current decayed to 20 A within 1 ms. However, in Fig. 4 (e) the current decayed only to 5 kA before the hot spot temperature reached 400 K, thus terminating the computation. In Fig. 4 (b)-(d), the current decays to 20 A in 0.1 s, 0.4 s and 0.6 s with inductances 0.816 mH, 8.16 mH and 15 mH, respectively. However, in Fig. 4 (d) it can be seen, that the quench detection voltage of 50 mV is not possible with the inductance of 81.6 mH, because the hot spot temperature reached 400 K before the current decayed to 4 kA. In addition, time elapsed from the initiation of the quench to the quench detection was 54.4 ms, 60.3 ms and 63.6 ms with quench detection voltages of 10 mV, 30 mV and 50 mV, respectively.

Fig. 5 presents the hot spot temperature as a function of inductance with different quench detection voltages. Longer magnets have higher inductance, and by plotting the hot spot temperature as a function of inductance we can assume the maximum magnet length that can be protected without exceeding the maximum applicable terminal voltage, which was in this case 900 V. Fig. 5 shows, that the maximum inductance with this type of Roebel cable is close to 50 mH with the quench detection threshold voltage of 50 mV. With inductances below 50 mH the hot spot temperature can be limited to under 400 K according to FEA, which can be considered safe from the HTS magnet point of view. However, the maximum actually allowed hot spot temperature is not known. If the magnet inductance is above 50 mH, higher protection resistance value has to be exploited if other protection schemes are not available. This increases the terminal voltage of the magnet. Thus, when considering the maximum length of the

Fig. 4. Current decay as a function of time. Varying inductance was used, i.e. a) 8.16 μ H, b) 0.816 mH, c) 8.16 mH, d) 15 mH and e) 81.6 mH. Solid line, dashed line and dotted line present the quench detection voltages of 10 mV, 30 mV and 50 mV, respectively.

magnet similar simulations should be scrutinized to estimate the hot spot temperatures in a magnet with different values of protection resistance. Further, for long length HTS magnets protection schemes should be adopted from LTS magnet or new schemes should be innovated.

Fig. 5. Hot spot temperature as a function of inductance of the magnet with different values of quench detection voltage: a) 10 mV, b) 30 mV and c) 50 mV. Dashed line presents MIITs computation and solid line FEA results.

IV. CONCLUSIONS

We simulated with FEA and MIITs computations the hot spot temperatures in an HTS magnet, designed to be built using the REBCO Roebel cable. In particular, the difference between the two methods with varying quench detection threshold voltages and magnet inductances was under investigation. Furthermore, we studied the maximum inductance of the magnet protected only with a dump resistor.

The hot spot temperature differences between FEA and MIITs, while being always higher with MIITs, varied from 60 K to 150 K with inductances from 8.16 μ H to 81.6 mH, respectively. Similar results were obtained with quench detection threshold voltages of 10 mV, 30 mV and 50 mV. Temperature differences of 100 K are rather large for quench studies, thus, MIITs concept seems unreliable when considering hot spot temperatures in HTS magnets protected with only dump resistors. However, MIITs concept could be usable when quickly comparing different magnet designs.

The hot spot temperatures in the magnet were also presented as a function of inductance. Usually the magnet inductance is given as H/m, thus, by presenting the hot spot temperatures in this manner gives an estimate if the magnet of certain length can be protected using a protection resistance or not. In this particular case the maximum inductance of the magnet was 50 mH, which resulted in a hot spot temperature of 400 K, which can be considered as safe operation with HTS magnets, however, this is debatable. Similar study is recommended when designing a magnet with certain length and protection resistance value to observe hot spot temperatures within a quench scenario.

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