How to Computationally Determine the Maximum Stable Operation Current of an HTS Magnet

Janne Ruuskanen, Antti Stenvall, Valtteri Lahtinen, Jeroen van Nugteren, Glyn Kirby, and Jaakko Murtomäki

***Abstract*—The short-sample critical current is only an indicative property for the maximum current a magnet can be continuously operated with. This was especially visible in the experiments of one of the world's first Roebel-cable based HTS dipole magnet prototype built and tested at CERN in 2017 where the thermal runaway developed very slowly in many cases. Consequently, the maximum stable operation current could be overstepped and stable operation could be recovered by lowering the current below the maximum of the stable range again. It is non-trivial to quantitatively predict this behaviour from the critical current measurements which are observed under specific cooling conditions and based on an arbitrarily selected electric field criterion for the critical current. To make more rigorous predictions on the maximum stable operation current, one needs to consider in detail the interplay of cooling over the magnet surface and heat generation in the winding. This paper presents a methodology to determine the maximum stable operation current for a given magnet, as well as studies its mathematical background. Insight to this problem comes from the Roebel-cable based dipole magnet studied at CERN during 2017.**

***Index Terms*—HTS magnets, Modeling, Finite element methods, Optimization**

I. Introduction

REBCO based high temperature superconductors (HTS) have prospects for producing magnetic fields beyond 20 T at low temperatures. Therefore, they enable a field range that cannot be reached with low temperature superconductors. Possible applications are high frequency NMR devices and high-field accelerator magnets. Currently, the use of REBCO based magnets in future accelerators is under consideration at CERN. [1]

Recently, a project EUCARD-2 [2] was finished with the aim of demonstrating the performance of HTS based accelerator magnet prototype. In the project, a Roebel-cable [3] based HTS dipole-magnet, Feather-M2 depicted in Fig. 1, was designed and built. The magnet was tested for the first time in 2017. The test results were presented in [4]. During the measurements, unexpected behavior was observed: the magnet could be operated at higher currents than the short sample critical current measurement predicted. This behavior is believed to be linked with the measured low n-value, which can be typical for Roebel-cables. However, the research problem on predicting the maximum stable operation current is clearly related to the thermal balance between the heat generation in the winding and the cooling of the magnet. This is different to magnets made from low temperature superconductors (LTS) where maximum currents can be predicted from near-adiabatic short-sample currents. The possibility of operating an HTS magnet at currents above its short sample critical current seems to be related to the cooling and gradual $V-I$ dependency.

Consequently, the critical current concept, based on arbitrarily selected voltage criterion, does not work for HTS coils having gradual $V-I$ dependency, as reported in [5] and already by Ishiyama *et al.* in [6] where they proposed a definition for the coil's maximum current to be based on the balance between the heat generation and cooling in the coil. Their approach was for a cryocooler-cooled system, hence the cooling power could be obtained directly from the cooler's cooling curve. However, in modelling thermodynamics in fluid cooled HTS coils, it is necessary to take the local cooling into account. Several different cooling models are utilized for example in [7], where the thermal stability of HTS composite tapes was numerically modelled.

In this paper, a method for computationally determining the maximum stable operation current is presented. We scrutinize the helium gas cooled Feather-M2 to demonstrate the feasibility of the proposed methodology. In the method, an optimization problem is formulated and solved to compute the maximum stable operation current. The method is based on the thermal model detailed in [8]. Using this methodology, we investigate the influence of cooling efficiency and cable properties on the maximum stable operation current. The paper is outlined as follows. Next, the methodology, utilized for determining the maximum stable operation current of an HTS magnet, is discussed. Then, the simulation results are presented with appropriate discussion, and finally, conclusions are drawn.

II. Methodology

This section reviews first the thermal model detailed in [8]. Then, we present a concept for the stability of HTS magnets which does not seem to depend on short-term disturbances of low magnitude, on contrary to LTS magnets [9], [10]. Finally, we present a mathematically rigorous way to find the maximum stable operation current of an HTS magnet.

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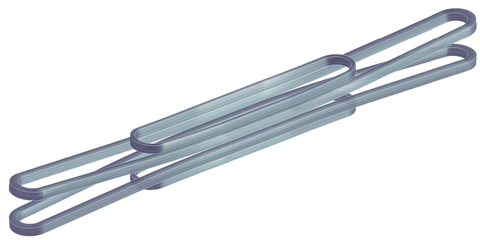

Fig. 1. Depiction of the dipole magnet Feather-M2. Both of the poles, Feather-M2.1 and Feather-M2.2 consist of two racetrack shaped coils, a longer and a shorter one.

A. *Computational model*

In this work, a simulation tool for performing thermal simulations for superconducting magnets was utilized. The discretization method is based on an assumption on homogeneous temperature in the cable's cross-section. Therefore, the temperature in the magnet can be modelled on 1-dimensional domain. The equation to be solved is

$$C_{\mathrm{V}} \frac{\mathrm{d}}{\mathrm{d}t} T = \frac{\mathrm{d}}{\mathrm{d}x} \left(\lambda \frac{\mathrm{d}}{\mathrm{d}x} T \right) + Q^{+} + Q^{-} + Q^{\parallel}, \tag{1}$$

where T and λ represent the temperature along the cable and the thermal conductivity in the cable's longitudinal direction, respectively. The terms C_{V}, Q^{+}, Q^{-} and $Q^{\parallel}$ represent the volumetric heat capacity, the volumetric heat generation, the volumetric cooling and the heat transfer between the cable turns, respectively. In this paper, we only revise the terms Q^{+} and Q^{-}, which are essential for understanding the methodology presented and utilized in this work. Details on discretizing and solving (1) are presented in [8], [11].

The heat generates in the cable's superconducting (sc) and in the normal conducting (nc) fractions, f_{sc} and f_{nc}, respectively. Hence, the heat generation in the cable can be expressed as

$$Q^{+} = f_{\mathrm{sc}} E_{\mathrm{sc}} J_{\mathrm{sc}} + f_{\mathrm{nc}} E_{\mathrm{nc}} J_{\mathrm{nc}}, \tag{2}$$

where the current density in the superconducting fraction and in the normal conducting fraction of the cross-section are $J_{\mathrm{sc}} = I_{\mathrm{sc}}/A_{\mathrm{sc}}$ and $J_{\mathrm{nc}} = I_{\mathrm{nc}}/A_{\mathrm{nc}}$, respectively. Here $I\_$ refers to current and $A\_$ to area. The electric field in the superconducting material E_{sc} is expressed using the power law as

$$E_{\mathrm{sc}} = E_{\mathrm{c}} \left(\frac{I_{\mathrm{sc}}}{I_{\mathrm{c}}} \right)^{n}, \tag{3}$$

where E_{c} and n are the electric field criterion and the n-value, respectively.

In the cable's longitudinal direction, the local critical current I_{c} is computed by integrating the critical current density function J_{c} over the superconducting fraction of the cable's cross-section A_{sc} as

$$I_{\mathrm{c}} = \int_{A_{\mathrm{sc}}} \alpha J_{\mathrm{c}}(T, \hat{\mathbf{B}} I)\ \mathrm{d}A,$$

where $\hat{\mathbf{B}}$ is the magnetic flux density per magnet's unit current. This means that that assumption on linear $\mathbf{B}(I_{\mathrm{op}})$, where I_{op} is the magnet's operation current, dependency is deployed. Moreover, a J_{c} scaling law is scaled with α to represent the J_{c} characteristic of our application. We utilize the scaling law presented in [12].

The electric field in the normal conducting material composite is modelled using

$$E_{\mathrm{nc}} = \rho_{\mathrm{nc}} J_{\mathrm{nc}},$$

where ρ_{nc} is the resistivity of the normal conducting fraction [13]. Furthermore, our assumption is that $E_{\mathrm{sc}} = E_{\mathrm{nc}}$ everywhere and hence I_{sc} and $I_{\mathrm{nc}} (= I_{\mathrm{op}} - I_{\mathrm{sc}})$, where I_{op} is the operation current, can be solved.

As emphasized already, it is necessary to take the cooling into account in the modelling. In the utilized computational model, the cooling in the winding is modelled using

$$Q^{-} = h \frac{T_{\mathrm{op}} - T}{c}, \tag{4}$$

where $(T_{\mathrm{op}} - T)$ is the temperature difference between the coolant and the winding, respectively. The parameter h represents heat transfer coefficient. The coefficient c is defined as $c = A/p$, where A is the the cross-section area of the homogenized cable and p is the wetted perimeter of the cable's cross-section.

B. *Stability concept*

In this work, we define the stability of HTS magnet by investigating the interplay between heat generation and cooling in the winding. This concept was proposed in [6] and utilized already at least in [8].

The heating power P and the cooling power C in the magnet volume are used to determine, whether the magnet is thermally stable or not. The heating power represents the power at which heat is generated in the winding volume Ω, and is computed as

$$P(t) = \int_{\Omega} Q^{+}\ \mathrm{d}\Omega = A \int_{0}^{L} Q^{+}\ \mathrm{d}x, \tag{5}$$

where L is the cable length, i.e. $[0, L]$ form the modelling domain at which (1) is solved. We used adiabatic boundary conditions at 0 and L in this work. The counterpart of heating power, the cooling power, is computed as

$$C(t) = \int_{\Omega} Q^{-}\ \mathrm{d}\Omega = \int_{0}^{L} ph \left(T_{\mathrm{op}} - T \right)\ \mathrm{d}x. \tag{6}$$

The cooling power represents the cooling power in the magnet volume due to the heat flux between the surface of the winding and the coolant.

Based on the quantities P and C, we define a magnet to be thermally stable according to the following definition.

Definition 1. A magnet, operated in constant conditions $(T_{\mathrm{op}}, I_{\mathrm{op}})$, is thermally stable if and only if $\exists t_0 > 0$ such that

$$\left(P + C \right)(t) \leq 0,\ \forall t \geq t_0. \tag{7}$$

Corollary 1. At constant operation conditions,

$$\exists t_0 > 0 \text{ s.t. } \left(P + C \right)(t_0) \leq 0 \ \Rightarrow\ \left(P + C \right)(t) \leq 0,\ \forall t \geq t_0.$$

In summary, in constant operation conditions, we can determine, whether the magnet is stable or not by computing if there is a time when the balance between the heating and the cooling exists. This is computationally possible to achieve unlike testing the balance when time goes to infinity.

C. Determining the maximum stable operation current

The maximum stable operation current $I_{\rm mas}$ of an HTS magnet can be determined by solving an optimization problem. The formulation of the problem is intuitive: maximize the operation current such that, the magnet is stable. Hence, the problem can be expressed as

$$\begin{aligned} \max \quad & I \\ \text{s.t.} \quad & (P+C)(t_0) \le 0 \end{aligned} \tag{8}$$

where the non-linear inequality constraint define the solution of the optimization problem to be feasible, only if the current I, results in stable magnet operation as defined in Definition 1. As the stability criterion, the result of Corollary 1 is utilized.

III. Results and discussion

In this section, we utilize the presented methodology for determining the maximum stable operation current of the HTS magnet, Feather-M2. We let this simulation result be the reference case for the following three parametric studies, where the model parameters n, α and h were varied and $I_{\rm mas}$ computed in order to investigate the influence of those parameters on the stability of the magnet. Moreover, in all of the simulations that are next presented we utilize the parameters listed in Table I unless otherwise stated. The model

TABLE I
Simulation parameters.

parameter	value	unit	description
α	0.17		scaling factor of J_c scaling law
n	2.8		n-value
E_c	109	μV/m	electric field criterion
h	85	W/m^{2}K	heat transfer coefficient
t_0	200	s	stability criterion time
$T_{\rm op}$	21	K	coolant temperature

parameters $\mathbf{x} = [\alpha \; n \; E_c \; h]$ were obtained as a solution of an inverse problem $E = \mathrm{M}(\mathbf{x}, I_{\rm op})$, where the thermal model M describes the relationship between the model parameters and the measured average electric field E in the magnet due to operation current $I_{\rm op}$. This process is detailed in [8]. These particular values for the model parameters were achieved for the data shown in Fig. 2, where the model predictions $\mathrm{M}(\mathbf{x}, I_{\rm op})$ are compared with the measured data E.

A. Reference case

The $I_{\rm mas}$ of the reference case was solved using the parameters listed in Table I. The obtained solution for $I_{\rm mas}$ was 5162 A. Fig. 3 shows the maximum temperature $T_{\rm max}$ and the power balance $P + C$ in the magnet as a function of

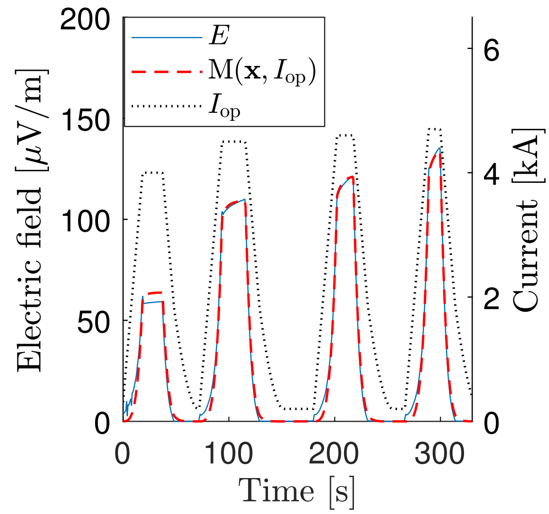

Fig. 2. Measured and simulated average electric field in the magnet and corresponding magnet operation current $I_{\rm op}$ as a function of time. Figure adopted from [8].

time for the three different operation currents $0.99 I_{\rm mas}$, $I_{\rm mas}$ and $1.01 I_{\rm mas}$ from left to right, respectively.

The results show that the maximum stable operation current is within 1% from the simulated $I_{\rm mas}$. At 1% lower operation current, the maximum temperature in the magnet stabilized to 3.1 K lower value (30.34 K) than at simulated $I_{\rm mas}$. However, when the operation current was increased to 1% above the $I_{\rm mas}$, thermal runaway occurred before 100 s simulation time was reached.

As seen, the thermal runaway develops very slowly (in tens of seconds rather than in milliseconds like with LTS windings) when $I_{\rm op}$ is slightly above the stable operation current range. Therefore, in terms of magnet protection, there is plenty of time to react before reaching temperatures that might damage the magnet. Similarly, one could operate for a short period of time above the maximum stable operation current and return to safe range without a quench and magnet de-energization. This kind of operation is typically not possible with LTS magnets.

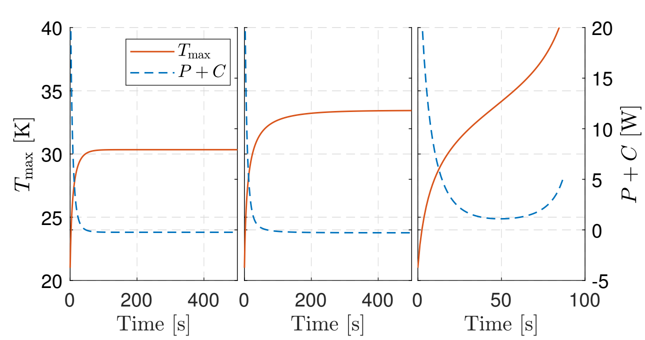

Fig. 3. The maximum temperature and the power balance as a function of time in the magnet at three different operation currents. The figures from left to right correspond to $I_{\rm op}$ of $0.99 I_{\rm mas}$, $I_{\rm mas}$ and $1.01 I_{\rm mas}$, respectively.

B. The effect of n-value, α and h on I_{mas}

The maximum stable operation current was computed as a function of n-value, α and the heat transfer coefficient. By performing these parametric analyses, we simulated, how the cable properties, related to n and α, and the cooling efficiency, related to the heat transfer coefficient, affect to the maximum stable operation current of the magnet.

Fig. 4 shows that I_{mas} decreased in this case as a function of n-value. This can be explained as follows. For lower n-values the heat generation is more gradual and therefore it is possible to balance P with C up to operation currents above 6 kA with $n = 2$. At high n-values, I_{mas} decreased gradually down to 3550 A. This is due to more aggressive heat generation with higher n-values which the cooling cannot balance at as high operation currents as in case of lower n. As a conclusion, lower n-value results in higher I_{mas} but more heat is generated at lower currents than in case of high n. Consequently, more cooling power is required in order to balance the heat generation if the cable has low n-value.

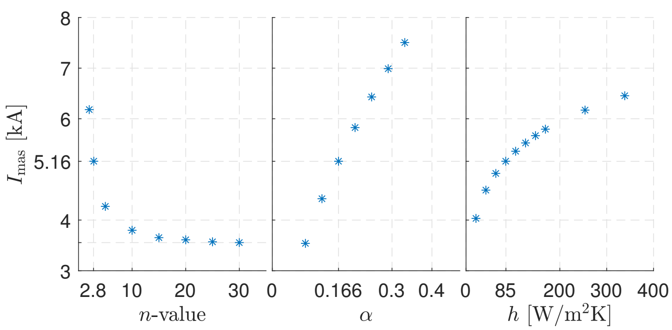

Fig. 4. From left to right, respectively, the maximum stable operation current as a function of n-value, α and the heat transfer coefficient.

The influence of α and h on I_{mas} is more obvious. For cable, having higher critical current density, I_{mas} was higher. Similarly for higher heat transfer coefficient, I_{mas} was higher but the dependency was not as linear as in case of α. These results indicate that I_{mas} would saturate at some point if h was increased to a value high enough. As a conclusion, with more powerful cooling system, low n-value or with cable having higher J_c, the magnet could be operated at higher operation currents.

In summary, as expected, magnet's I_{mas} was higher for higher h and α. The n-value dependency was not trivial: for lower n-values, I_{mas} was higher and for higher n-values, above 20, stable magnet operation was not possible anymore above operation currents of 3.6 kA due to more aggressive heat generation, the cooling could not compensate anymore.

IV. Conclusions

Due to the slanted $V - I$ behavior of HTS based magnets, determining the maximum current based on voltage criterion is arbitrary. A concept for determining the maximum current based on investigating the interplay between heat generation and cooling in the winding is adapted in this paper. Using the concept, the maximum stable operation current was determined by formulating and solving an optimization problem. Three parametric studies were performed on the heat transfer coefficient h, the scale α of J_c scaling law and cable's n-value.

According to the results, with higher values of α and h, higher I_{mas} was predicted. Conversely, higher I_{mas} was predicted for lower n-values while for higher n, I_{mas} decreased to a value around 3550 A. This behavior is due to the more aggressive heat generation at higher n than at lower n. Consequently, for lower n and hence more gradual heat generation, the magnet can be operated at overcritical currents, above E_{c}. We also found out, like the experiments demonstrated too, that there are tens of seconds time to react before thermal runaway, even if operation current is above I_{mas}.

Further, there is still lot to explore on this topic even with the current model, for example, how do the investigated parameters influence on the allowed time to operate with a current above I_{mas}. In addition, the optimization problem could be solved, and I_{mas} predicted, in case if a thermal disturbance occurred in the magnet during the simulation. Then the maximum stable operation current would be such that the magnet would remain remain stable even if the disturbance occurred.

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