Challenges in the Thermal Modeling of Quenches With ROXIE

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Abstract—The simulation of thermal processes in a superconducting coil during resistive transition is an intricate problem. A detailed thermo-hydraulic modeling comes at a high computational cost and suffers from the large number of empirical parameters. We present a macroscopical approach, covering the most relevant features while providing enough flexibility to gauge the material parameters with measurements. By combining the thermal model with numerical field computation, effects can be simulated that are otherwise difficult to measure, e.g., turn-to-turn voltages, quench propagation and recovery. The thermal model recently implemented in the CERN field computation program ROXIE is validated by means of measurements on model and prototype magnets, as well as data taken during the hardware commissioning of the LHC.

Index Terms—Helium, quench simulation, thermal model.

I. INTRODUCTION

NUMERICAL simulations are carried out for the prediction of the quench behavior in the design phase of superconducting magnets. They can also serve for the analysis of quench measurements. In the first case, an optimum protection scheme can be developed, ensuring safe and stable operation of the prototype. In the latter case, hypotheses on the cause of unusual events can be tested. The simulation can also help to study the sensitivity of design features and material parameters.

For the study of quenches and quench protection during a current ramp (companion paper [1]), we have extended the ROXIE [2] quench program by an improved cooling model and the simulation of helium in the conductors. In this paper we present the main aspects of these improvements and give the results of recently performed quench calculations.

The simulation of thermal processes at cryogenic temperatures is an intricate problem. Material properties at cryogenic temperatures and under pressure are often difficult to obtain. The highly nonlinear dependence of these parameters on the magnetic flux density and temperature is a challenge for numerical stability. Accurate modeling of the thermal processes in Rutherford-type cables comes at high computational cost, see for example [3] for 2-D and [4] for 3-D models. Models on the level of strands are therefore not applicable at the level of the simulation of entire magnets with their external quench protec-

tion circuits. Reduced complexity in the modeling may, however, result in a loss of accuracy and a reduced range of validity.

In this paper we discuss an improved thermal model recently implemented in the ROXIE quench module. The features are demonstrated by simulations of a quench in an impregnated coil (wound from a ribbon-type conductor) and for the case of a quench recovery in an LHC insertion quadrupole.

In Section II we present the ROXIE quench model. In Section III we introduce the thermal network model based on an approach in [5]. Section IV shows results and addresses limitations of the model.

II. THE ROXIE QUENCH MODULE

We give an overview of the different models interacting in the ROXIE quench module. A detailed description of the numerical aspects of quench simulation with ROXIE is given in [6].

The local field distribution in a coil is calculated by means of the coupling method between boundary and finite elements (BEM-FEM). Eddy-current losses in the cable are calculated from the local field sweep. We calculate interfilament coupling currents that are induced in the twisted superconductor-copper matrix of a strand and consider interstrand coupling currents that are induced in a Rutherford-type cable. The coupling-current time-constants are influenced by the copper resistivity, contact resistances between the strands, and geometric conductor parameters, all of which are input parameters to the simulation. The BEM-FEM field model and the coupling-current models are weakly coupled by an iteration loop [7].

The magnet is connected to a generic external network that consists of a current source, bypass-diode with adjustable threshold voltage and forward resistance, and an energy extraction system with switch and dump resistor. The magnet itself is represented by its electrical resistance and the current-dependent differential inductance. The different electrical, magnetic, and thermal models used in the ROXIE quench module are depicted in Fig. 1.

III. THE THERMAL MODEL

a) *The thermal network:* The thermal problem is described by the heat-balance equation:

$$\rho(T)c(T,B)\frac{dT}{dt} = P + \operatorname{div}(\kappa(T,B)\operatorname{grad} T), \quad (1)$$

where T is the temperature and B the applied magnetic flux density. The external heating power is given by P . The material parameters are the specific heat c , the thermal conductivity κ , and the mass density ρ .

Introducing finite volumes, (1) can be transformed into a network equation with lumped elements. In the coil cross-section, each conductor constitutes one node in the network, whereas the

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Fig. 1. Different models interacting in a quench simulation. Clockwise starting at 12h00: (a) electrical network of powering and protection elements, (b) geometrical model of the coil, analytical field calculation, (c) BEM-FEM model of the nonlinear iron yoke, (d) network model of inter-strand coupling currents, (e) magnetization model of inter-filament coupling currents, (f) magnetization model of persistent currents, (g) thermal network model of heat conduction and quench heaters, (h) fit of the critical surface of the superconductor.

longitudinal subdivision is a user supplied parameter (it is one for a 2-D calculation).

The network equation is solved by means of an explicit Runge-Kutta scheme of 4th order with adaptive time stepping. The step-size is controlled by a modified Collatz method [8]. Due to extreme nonlinearities of material properties in T and B , the algorithm was modified by a lower bound on the step-size. Consequently, calculations have to be validated with half the minimum step-size to check for numerical stability.

Since in the transverse plane the temperature across each conductor is assumed to be constant, current redistribution between the strands [4] cannot be considered.

The insulated conductor is treated as a composite material with homogenized material properties. The conductor's longitudinal heat conductivity is deduced from the electrical resistivity ρ_E by the Wiedemann-Franz law [9]

$$\kappa = \frac{LT}{\rho_E}, \quad (2)$$

where L denotes the Lorentz-number (approx. $2.45 \cdot 10^{-8} \text{ V}^2 \text{ K}^{-2}$). Transversally, the heat conductivity of the insulation is evaluated at the mean temperature of two adjacent conductors.

Fig. 2. Heat capacity of helium per volume as used in the model (derived from [10]). The dashed line indicates the assumed pressure p and the dotted line the resulting density ρ .

We consider the following heat sources: Ohmic losses in the normal-zone of the superconducting cable, induced losses from inter-filament and inter-strand coupling currents [7], and quench heaters. Book-keeping of the individual heat sources and of the heat conduction allows us to determine the cause of quench for each thermal element in the model. We can thus distinguish between local quench due to quench-back, quench propagation, or quench heaters (see Fig. 4).

b) Thermal properties of helium: Superfluid helium features two phases. Phase I for temperatures above the lambda-point (approx. 2.17 K at saturated vapor pressure) and phase II below. The heat conductivity of phase II helium exceeds the conductivity of copper by orders of magnitudes. Phase I liquid helium and super-critical helium have negligible thermal conductivity. The specific heat of both, Phase I and II helium exceeds that of copper or niobium-titanium by orders of magnitude. Super-critical helium, however features a relatively small specific heat compared to copper. Thus, for temperatures below the phase transition and below the lambda-point, the “confined” helium (in the voids of Rutherford-type conductors) needs to be considered.

We make the following assumptions on mass- and volume balance inside the conductors: Below the lambda-point the mass density and total mass of helium remains constant (zone 1 of Fig. 2). At temperatures above this point the helium is adiabatically compressed until the local pressure in the conductor rises up to a limit p_0 (zone 2). In zone 3 the helium is heated at constant pressure, i.e., mass flows out of the conductor. Fig. 2 shows the specific heat (for constant volume) and mass density of helium in a conductor as derived from measurements in [10]. The helium content under nominal operation conditions is a user-supplied parameter in the simulation and depends on the compaction of the cable.

Below the lambda-point, heat conduction between adjacent conductors is determined by the helium percolating across the insulation and by the conductivity of the conductors. The

thermal conductivity of superfluid helium being infinite at first approximation, the conductivity is determined by the conductor material, i.e., mostly by the copper in the strands. Above the lambda-point, the heat conductivity of helium is neglected in our model.

The model does not consider the energy absorbed by the helium phase-transitions. The confined helium is assumed to be in close contact with the strands. Variations in the thermal contact due to nucleate and especially film boiling are not considered.

c) *Conductive cooling*: In the presented model, cooling is included by additional nodes of fixed temperature. Therefore the cooled face of the cable and the distance to the cold surface have to be specified. The thermal conductance to this heat sink is calculated in the same way as between conductors. This allows to simulate the heat extraction without considering an increase of the bath temperature or the limitation of the heat exchangers to extract more than a certain amount of heat.

d) *Quench heaters*: Quench heaters are modeled as effective heat sources inside the cable. The heaters are described by three parameters, effective initial heating power P_0 , internal delay T_0 , and the discharge time constant τ given by the heater powering circuit. The parameters P_0 and T_0 are set such that the quench heater delay, i.e., the time between firing a heater and the occurrence of a quench, can be reproduced over the full current range.

IV. RESULTS

A. 3-D Thermal Propagation—MCBX

The 3-D thermal propagation of a quench is studied for the LHC MCBX corrector magnet [11]. The MCBX consists of two nested independently powered dipoles. We consider the outer dipole only. The magnet is wound from a 7-strand ribbon-type conductor using a strand of the LHC MB inner layer cable rolled into a rectangular form. The strands are connected in one coil end such that each radial layer of strands is connected in series. This allows for radial and azimuthal quench propagation within a coil block and for longitudinal propagation within each radial layer of strands. The coil is fully impregnated so that no cooling needs to be considered. The magnet is operated at 1.9 K and the quench occurs at 734 A. For the present simulations, the magnet is neither protected by quench heaters nor by a dump resistor. The voltage across the power supply is neglected.

Fig. 3 shows how a quench originating on the upper pole propagates through the coil. Both, measured and simulated turn-to-turn quench propagation delay, yield 4 ms. The longitudinal quench propagation velocity is calculated to be 18 m/s which is in good agreement with measurements [12].

By comparing the integrated heat flux from neighboring elements, induced losses, and quench heaters, the reason for a conductor to quench can be derived. Fig. 4 shows that only a few turns are quenched by induced losses. Especially the conductors in the low field region (see arrow) are quenched by heat transfer.

Fig. 5 shows the measured [13] and simulated current decrease which match nicely up to 0.3 s. Then the measured current decreases slower than the simulation. Due to the short overall length of the magnet, the 3-D saturation of the iron yoke

Fig. 3. Quench propagation in the MCBX outer coil: The 3D model is displayed from the non-connection side of the coil and longitudinally compressed by a factor of 10. The quench started in upper pole, inner most turn, close to the coil end. (left) Temperature distribution after 0.1 s. The quench propagated longitudinally and transversally in the upper most block. It spread to the block below over the connection-side. (right) Temperature distribution at the end of the quench. The lower pole shows an elevated temperature due to induced losses. The maximum temperature is 180 K.

Fig. 4. Cause of quench in the MCBX: The light colored conductors quenched due to heat transfer from other quenched conductors, the dark colored conductors quenched due to induced losses.

Fig. 5. Current decrease during quench in the MCBX: Simulation and measurement match well up to 0.3 s.

is likely to influence the inductance and thus the current decay in a different way than predicted from 2-D calculations. This problem will have to be addressed in future simulations.

Fig. 6. Current decrease in the MQY after triggering the quench heaters at a current level of 80 A. The two dashed lines correspond to the measurement of the currents of the two apertures. The full line represents the simulation.

Fig. 7. Temperature margin to quench for one coil of the MQY. Note the logarithmic time scale.

A good match between simulation and measurements could be obtained without gauging the material properties, since neither cooling nor helium need to be considered.

B. Quench Recovery—MQY

During a test of the LHC MQY quadrupole magnets [11], quench heaters were fired at a magnet current level of only 80 A (compared to a nominal current of 3610 A). The current measurement [14] show clearly two different slopes indicating a quench in the magnet and a later recovery. The ROXIE quench model is used to reproduce this effect.

The MQY is a double aperture magnet with quench heaters on the outer radius of the coils as well as between the second and the third coil layer. The coils of both apertures are powered independently. At low currents, the two apertures are magnetically decoupled.

For the simulation, the effective power of the quench heaters has been varied until a quench is triggered at 80 A and the slope of the current decrease is consistent with the measurements. Furthermore, the cooling is set such that a recovery from quench is

within reach after few seconds. Fig. 6 shows both, measured and simulated current decay. Note: In the measurement the current of both apertures are shown. Fig. 7 shows the change of temperature margin to quench over the conductors of one pole of the magnet during the heater discharge. The quench occurs 0.1 s after firing the heaters and the conductors recover 1–3 s later. By means of this simulation details of the quench recovery which evade direct measurements can be studied. The results have been obtained by gauging model parameters within their reasonable range.

V. CONCLUSION

We present a thermal model combined with numerical field computation that allows the reproduction of measurements by gauging of empirical parameters. The models can be used to study quench protection schemes already in the conceptual design phase of future magnets. The quench simulation program also helps in the interpretation of unexpected quench behavior and the definition of test campaigns. It is implemented in a user friendly way within the ROXIE program package.

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