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MODELLING OF THE QUENCH PROCESS FOR THE OPTIMISATION OF THE DESIGN AND PROTECTION OF SUPERCONDUCTING BUSBARS FOR THE LHC

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Abstract

The superconducting busbars powering the LHC magnets are highly stabilised with copper to reduce the probability of a quench starting in a busbar and to avoid excessive temperatures after a quench during current discharge. In order to determine the required copper stabilisation and the parameters of the protection system a finite difference program has been developed. The program numerically approximates the heat balance equation and evaluates the temperature profile after a quench as a function of time and space. The approach emphasises the modelling of heat transfer into helium. The evaluation of the temperature includes the entire quench process, i.e., the time for quench detection and the current decay.

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The superconducting busbars powering the LHC magnets are highly stabilised with copper to reduce the probability of a quench starting in a busbar and to avoid excessive temperatures after a quench during current discharge. In order to determine the required copper stabilisation and the parameters of the protection system a finite difference program has been developed. The program numerically approximates the heat balance equation and evaluates the temperature profile after a quench as a function of time and space. The approach emphasises the modelling of heat transfer into helium. The evaluation of the temperature includes the entire quench process, i.e., the time for quench detection and the current decay.

1 INTRODUCTION

The solution of the heat balance equation determines the temperature profile after a quench along a superconducting busbar as a function of time and space in presence of various cooling conditions. As the heat balance equation is not analytically solvable, a finite difference program has been developed in order to evaluate the required design and the parameters of the protection system of the different superconducting busbars that will power the various types of magnets of the LHC. Simulation studies of busbar quenches are necessary to scale experimental results from quenching prototype busbars [1] to the situation of a busbar quench in the LHC when the quench load increases up to an order of magnitude. The simulations allow to estimate the hot spot temperature for different copper stabilisations. The theoretical approach described here was also used to better understand experimental results of the quench propagation of the busbar cable powering the auxiliary magnets of the LHC [2].

2 THEORETICAL MODEL

The busbar is represented by N equidistant elements of length Dx with temperature T_i, cross-section A_i and wetted perimeter P_i. The busbar is treated as a homogeneous structure, i.e. the copper cross-section is the sum of the copper stabilisator (A^{St}_{Cu}) and the copper fraction of the superconducting cable ($f_{cu}A_{cable}$). The quench is initiated by a Gaussian temperature profile of temperature T_{init} and width σ_T . In case of the busbar the temperature as a function of time t and x is the solution of the one dimensional heat balance equation

$$\frac{d}{dx}\left(k(T(x,t))\frac{dT(x,t)}{dx}\right)A(x) - h^{He}(T(x,t),t)P(x) + G(T(x,t),t) = c(T(x,t))A(x)\frac{dT(x,t)}{dt};$$

with c being the heat capacity, k being the heat conductivity, h determining the heat transfer into helium, and G being the internal heat generation. $G(T(x, t))$ is given by

$$G(T(x,t),t) = \begin{cases} 0 & \text{if } T(x,t) \leq T_{cs}(t) \\ \rho_{cu}(T(x,t))\frac{I(t)^2}{A(x)}\frac{T(x,t)-T_{cs}(t)}{T_{crit}(t)-T_{cs}(t)} & \text{if } T_{cs}(t) < T(x,t) \leq T_{crit}(t) \\ \rho_{cu}(T(x,t))\frac{I(t)^2}{A(x)} & \text{if } T(x,t) > T_{crit}(t) \end{cases}$$

Heat is generated if the temperature exceeds the current sharing temperature T_{cs}. The current I is constant until the resistive voltage that increases in case of a propagating quench exceeds the detection threshold. The current then decays exponentially with a decay time constant τ_I. The cooling conditions are determined by the heat transfer from the busbar surface into the helium bath of temperature T_{bath}. The simple model (model 1) for the heat transfer coefficient h is

$$h_c^{He}(T(x,t),t) = a \cdot (T(x,t) - T_{bath})$$

A complex model (model 2) for transient heat transfer including Kapitza regime and film boiling requires more parameters [3]

$$h_c^{He}(T(x,t),t) = \begin{cases} 0 & \text{if } T(x,t) \leq T_{bath} \\ a_1 \cdot (T(x,t)^n - T_{bath}^n) & \text{if } T(x,t) \leq T_{n.boil} \\ a_2 \equiv h(T_{n.boil}) & \text{if } T_{f.boil} > T(x,t) > T_{n.boil} \\ a_3 \cdot (T(x,t)^m - T_{bath}^m) & \text{if } T(x,t) > T_{f.boil} \wedge t - t(T > T_{n.boil}) < t_{boil} \\ a_4 & \text{if } t - t(T > T_{f.boil}) > t_{boil} \end{cases}$$

with $T_{n.boil}$ and $T_{f.boil}$ being the temperatures of starting nucleate and film boiling, and t_{boil} being the time interval for burn-out.

The quench propagation velocity v_q is determined from the simulation result as the increase of the resistive zone with time. The hot spot temperature T_{max} and v_q for the given quench load can be compared with experimental results for calibration of the cooling model.

Since the heat transfer rate into helium is limited due to the heat conductivity of the insulation material, the temperature has to be evaluated separately for the cable surface T and the insulation layer surface T_{iso} to obtain a cooling model without fit parameters (model 3). Both heat balance equations are connected by heat conduction from the cable surface into the insulation layer.

3   SIMULATION STUDIES

3.1   Quench_propagation

An example of the quench propagation is shown in Fig.1. The simulation studies demonstrated that an
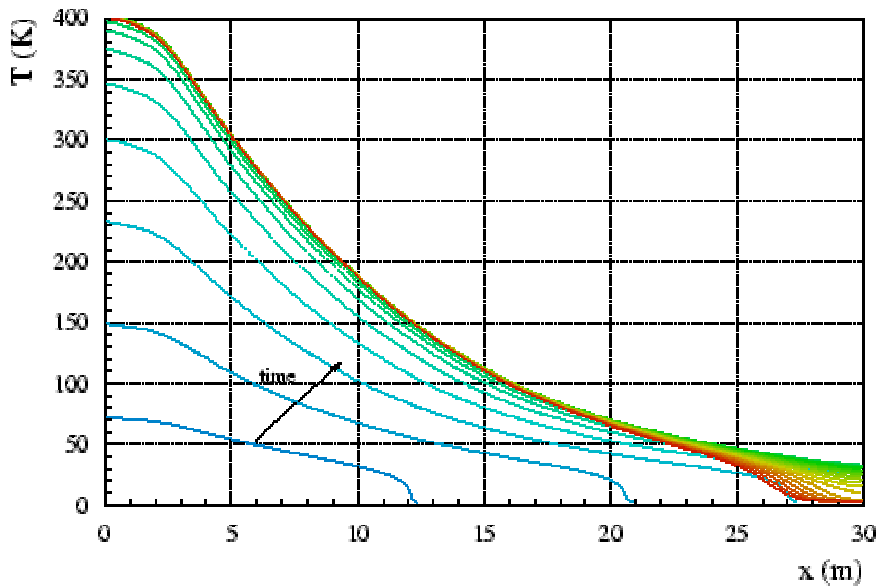
Figure 1: Temperature profile as a function of space and time showing the expanding normal conducting zone. The parameters for this simulation study are A_{tot}=258mm^2, U_{thres} =1V, I_0 =12.5kA, cooling conditions according to model 3. The quench was initiated with T_{init}=20K, σ_T =0.8m. The time interval between two curves in the figure is 25s.

increasing temperature at the quench origin always leads to an expanding normal conducting zone for realistic cooling scenarios and $A(x)\equiv A$. Otherwise the temperature decreases and recovery takes place. Due to the long time period of the quench process the hot spot temperature does not depend on the quench initialisation temperature. When the normal conducting zone is neither expanding nor shrinking the hot spot temperatures remains constant until the cooling conditions vary. This unlikely situation would increase the heat load on the cryogenic system. If the cooling power decreases the temperature will start to increase and the normal conducting zone will expand followed by quench detection and current decay. The limits for the copper cross-section of the busbars presented below ensure that no excessive temperatures will be obtained in such a case.

3.2   Calibration

The simulation model was calibrated using experimental results of prototype busbar tests [1]. The prototype busbar for the LHC main dipole magnets has a cross-section of A_{Cu}=296.5mm^2 and A_{NbTi}=6.5mm^2. The quenches were induced firing a spot heater immediately followed by a linear current discharge. The wetted perimeter was fitted for the cooling models 1 and 2 to obtain the measured quench propagation velocity. The simulated hot spot temperature was then compared with the experimental result for the measured quench load during the tests. When the complex cooling model is used and the insulation layer is taken into account (model 3) the wetted perimeter is not a fit parameter. If a small amount of helium is present in the busbar or in the insulation layer this helium fraction has to be included for adjustment of the model (model 3 adjusted).

model	variable	measurement	simulation
model 3	v_q	0.3-0.4 m/s	0.42 m/s
model 3 adjusted	v_q	0.3-0.4 m/s	0.36 m/s
	T_{max}, T_{bath}=1.9 K	55 K	60 K
	T_{max}, T_{bath}=4.2 K	76 K	80 K

Table 1: Comparison of simulation and experimental results. The parameters of the cooling model are a_1 =180 W/m4 , a_3 =100 W/m, n=4, m=1, t_{boil}=0.02 s. A helium fraction of 0.5 % of the total cross-section is used for the adjustment.

When the cross-section is dominated by the copper stabilisation the adjustment of model 3 is negligible which indicates the robustness of the theoretical approach (see Table 1).

3.3   Scaling and Detection

In order to evaluate the hot spot temperature after a bus bar quench in the LHC, the time required for quench detection and opening the extraction switches, and the time for the current decay (τ_I 100 s for the main dipole magnet circuit) have to be included. For that reason the experimental results of prototype busbars [1] have to be scaled. The detection time for various threshold levels was evaluated as a function of cooling conditions keeping the busbar cross-section constant. As the long term cooling conditions are not very well known, the hot spot temperature was estimated using the different cooling models. The maximal temperature differences are about 50 K at a 1 V detection level. Table 2 shows that a detection level of 1 V limits the hot spot temperature to tolerable values whereas a threshold of 5 V leads to excessive temperatures.

3.4   Required Copper Stabilisation

For a detection level of U_{det}=1 V the hot spot temperature after a quench for various copper cross- sections and operating currents was simulated for the busbars of the main dipole and quadrupole magnets. The simulation study includes modelling the heat transfer through an insulation layer of 200μm thickness and the complex cooling model.

Cooling model	Simulation parameter	P [m]	U_{thres} [V]	v_{quench} [m/s]	T_{max} [K]	T_{ad} [K]	zone [m]	Quench.load [A²s]	t_{det} [s]	U_{max} [V]
-	adiabatic		5	1.04	383	-	309	$1.38\cdot10^{10}$	45.6	16.9
1	simple model	0.0035	5	0.31	450	480	64	$1.49\cdot10^{10}$	86.1	8.5
2	$t_{boil}=20$ ms	0.0160	5	0.30	688	710	54	$1.69\cdot10^{10}$	68.1	11.3
2	$t_{boil}=\infty$	0.0069	5	0.30	576	780	55	$1.74\cdot10^{10}$	71.9	10.5
-	adiabatic		1	1.10	206	-	272	$1.05\cdot10^{10}$	22.6	6.6
1	simple model	0.0035	1	0.31	214	240	46	$1.13\cdot10^{10}$	50.0	2.6
2	$t_{boil}=20$ ms	0.0160	1	0.30	318	325	38	$1.28\cdot10^{10}$	40.0	3.7
2	$t_{boil}=\infty$	0.0069	1	0.30	261	355	37	$1.33\cdot10^{10}$	42.6	3.3
3	$l_{iso}=200\,\mu m$	0.072	1	0.36	297	334	49	$1.29\cdot10^{10}$	38.0	3.5

Table 2: Detection times and hot spot temperatures for a busbar quench in the LHC (A_{tot}=303 mm²). The wetted perimeter is the fit parameter for model 1 and 2. The used cooling model parameters are given in Table 1. T_{ad} is the adiabatic temperature calculated for the given quench load; zone is the expected maximum length of the normal conducting zone.

The minimum required copper cross-section to avoid temperatures higher than 400 K was found to be A^{MB}_{Cu} =240 mm² for the busbar powering the main dipole magnets and A^{MQ}_{Cu} =160 mm² for the busbar powering the main quadrupole magnets (τ_I^{MQ} =45s). Due to the shorter current decay time the copper cross-section of the busbar for the main quadrupole magnets is smaller. This reduction causes the quench detection time being only half as long with respect to the busbar for the maindipole magnets.

For a given quench load, the cooling reduces the hot spot temperature with respect to the adiabatically calculated temperature. For the LHC dipole busbars, the difference could be as large as 200 K. The hot spot temperature varies by less than 10 % for the different cooling models when the same detection time is assumed. When the various cooling models determine the quench detection time, the hot spot temperature varies by about 20 %.

4   CONCLUSIONS

The quench process of the busbars has been simulated using the finite difference method. The theoretical approach allows studying different cooling models including the heat transfer through the insulation layer. The adequate thresholds for the quench detection for the busbars powering the LHC main magnets and the required copper stabilisation to avoid overheating were determined. The developed program also allows the assessment of more complex geometries, for example the reduction of the busbar cross-section through lambda plates, etc.

5   ACKNOWLEDGEMENTS

References

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