Transient Stability Analysis of the SeCRETS Experiment in SULTAN

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Abstract—We present here the results of the analysis of the stability experiment SeCRETS, performed on two Nb_3Sn cable-in-conduit conductors with the same amount of total copper stabilizer, but different degree of segregation. The model used for the analysis, including superconducting strands, conductor jacket and helium, is solved with the code Gandalf™. We obtain a qualitative agreement of simulation results and experimental values. The simulation results confirm that in the operation regime explored in the experiment the segregated copper is not effective for stability. The details of the current sharing and the approximation taken for the transient heat transfer are shown to be critical for the interpretation.

Index Terms—Cable-in-conduit conductor, current sharing, heat transfer, transient stability.

I. INTRODUCTION

THE SEGREGATED Copper Ratio Experiment on Transient Stability (SeCRETS) has been successfully completed in the SULTAN facility at CRPP. The main aim of the experiment was to compare the stability performance of two Nb_3Sn cable-in-conduit conductors (CICC) prepared with identical cross sections but different location of the copper stabilizer, i.e., either fully included in the composite strands (conductor A) or partially segregated as pure copper wires accounting for 34% of the total stabilizer in the cable (conductor B). Two conductor sections, each about 13 m long, were series connected and wound as a bifilar single layer solenoid. A set of pulsed coils provided a transverse field to both conductors over 30 cm length. After heat treatment, the instrumented winding was inserted in the bore of SULTAN with background field B_{SUL} up to 11.3 T and operating current I_{op} up to 12 kA [1], [2].

The stability test under pulsed field was the key test for SeCRETS. After setting B_{SUL} and I_{op}, the temperature was adjusted to obtain in both conductors the same temperature margin, $\Delta T = T_{cs} - T_{op}$, where T_{cs} is the current sharing temperature and T_{op} the operating temperature. The pulsed coils were subsequently fired, producing a sinusoidal field variation with amplitude ΔB and period 65 ms. The amplitude of the field waveform was increased till one of the two conductor lengths quenched. The margin ΔT was then increased in the *weaker* conductor to allow further testing of the *stronger* conductor. These tests were repeated for several settings of

TABLE I
REFERENCE INPUT DATA

Parameter	Units	Conductor A	Conductor B
length	(m)	2	2
non-copper cross section	(mm^2)	30.24	29.89
copper cross section	(mm^2)	45.36	29.89[(1)]
cosine of cabling angle	(-)	0.9840	0.9893
jacket cross section	(mm^2)	46.37	46.37
helium cross section	(mm^2)	44.07	44.51
void fraction	(%)	36.8	37.2
cable wetted perimeter	(mm)	373	292
jacket wetted perimeter	(mm)	9.7	9.7
hydraulic diameter	(mm)	0.473	0.512
longitudinal strain	(%)	-0.725	-0.635
T_{c0M}[(2)]	(K)	17.3	17.7
B_{c20M}[(2)]	(T)	32.65	32.80
C_0[(2)]	$(AT^{0.5}/mm^2)$	7750	7515
copper RRR	(-)	107	95

NOTES:
[(1)] segregated copper not included
[(2)] fit parameters for Nb_3Sn critical properties [7]

operating current, operating temperature and helium massflow. Details on the experiment and the main results can be found in [2], [3]. In this paper we analyze the main results focusing on the dependence of transient stability on operating conditions such as current, temperature margin and helium massflow.

II. SIMULATION MODEL

We have performed the simulation of the SeCRETS stability test with Gandalf™, the CryoSoft code for the simulation of quench initiation and propagation in CICC with multiple cooling channels. The model at the basis of the code and the solution method are described in [4] and [5]. The components, i.e., strands, jacket and helium, are thermally coupled through convection on wetted surfaces (or contact perimeters) with a surface heat transfer coefficient h. The temperature is homogeneous in the cross section of the components and can vary only along the length. Standard models were used for the heat transfer and friction factor correlations. The code, as discussed later, was however modified substantially to take into

proper account the voltage–current relation of the cable in the calculation of the current sharing and Joule heat dissipation.

A. Cable Geometry and Operating Conditions

The reference input data is summarized in Table I. The length of conductor modeled is 2 m and its center coincides with the center of the heated zone. We have verified that the transient stability is decided shortly after the end of the field pulse, hence the boundary conditions at the end of the sample do not affect the result. It is therefore not necessary to model the full length of 13 m. Measured values of the helium inlet pressure and of the mass-flow are given as hydraulic boundary conditions. In both conductors the copper and noncopper cross sections used include a $1/\cos(\theta)$ correction due to conductor twisting by a cabling angle θ. While in conductor A the full copper cross section is considered, in conductor B the segregated copper cross section is neglected. Taking this choice we make the drastic assumptions that only the copper embedded in the strands participates to the current sharing. For this reason only the wetted perimeter of the strands is accounted for the heat transfer to helium. The heat transfer perimeter at the contact surface of strand and bundle is the geometric value, i.e., the sum of the wetted perimeters of the strands. The friction factor of the helium flow in the cable bundle is characterized by the correlation of Katheder [6]. The mesh consists of 200 linear elements and the minimum and maximum time steps used for integration are 1 μs and 10 μs, respectively. A first order method in time is applied for the integration. We checked that the simulations are numerically converged for this choice of solution parameters.

B. Pulsed Magnetic Field and Deposited Energy

In the experiment the energy is deposited in the cable by the AC loss caused by the sinus variation of the pulsed field, superimposed to the constant background field B_{SUL}. In the simulation we have considered the combined effect of the simultaneous field variation, affecting the critical properties of the superconductor, and of the energy deposition. We have taken for the pulsed field the following waveform:

$$B = \Delta B \sin \left(2\pi \frac{t}{\tau_q} \right) \tag{1}$$

where $\tau_q = 65$ ms is the period of the pulse and ΔB its amplitude. We further assumed that during this field pulse the AC loss is in fully developed (resistive) regime, so that the time dependence of the power dissipated Q is proportional to the square of the time derivative of the field dB/dt, or:

$$Q = Q_0 \left[\cos \left(2\pi \frac{t}{\tau_q} \right) \right]^2 \tag{2}$$

where Q_0 is a proportionality constant adjusted during the iterative search of the stability margin. In the model the heat is deposited uniformly in the cross section of the strands, and is constant along the length of the pulsed coils, i.e., between 0.85 m and 1.15 m.
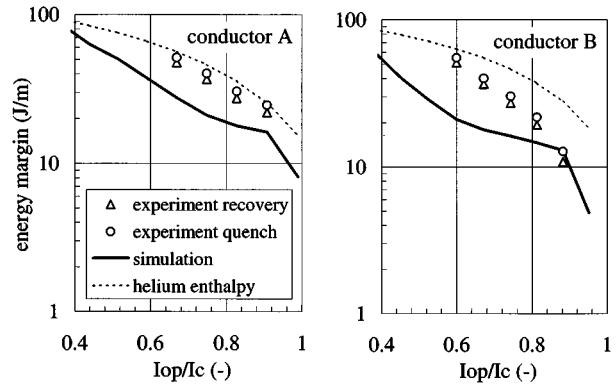

Fig. 1. Transient stability as a function of the ratio of operating to critical current for conductor A (left) and B (right) at a massflow of 3.5 g/s. The operating temperature is 6.2 K for conductor A and 6.6 K for B. The experimental results (symbols) are compared to the results of simulations (solid line). The helium enthalpy between the operating temperature and the current sharing temperature represents the ideal upper limit of the energy margin (dotted line).

C. Superconductor Properties

The critical current density J_c is fit using [7] and the coefficients of Table I. It was found in the experiment that the value of T_{cs} depends strongly on the value of the electric field E_0 at which the critical current is defined. The reason is that with a power-law exponent n of the order of 15, the voltage rise in the proximity of the critical current is relatively shallow and a considerable voltage can be sustained before thermal runaway. The difference in the T_{cs} deduced at 1 μV/cm and the temperature at which the thermal runaway takes place can be as large as 0.6 K. As most of the experimental runs were performed in a region where the temperature margin was below 1 K, this effect can be very important and had to be included in the model.

The model originally devised in Gandalf™ for the current sharing is equivalent to a value of n equal to infinity [5]. This results in a large underestimate of the stability margin. The calculation of the Joule heat contribution was thus modified to model the effect of a finite n. To this aim the electric field in the superconductor was modeled as is customary using a power law approximation:

$$E = E_0 \left(\frac{I_{sc}}{I_c} \right)^n \tag{3}$$

where E_0 is the electrical field used for the definition of the critical current I_c, I_{sc} is the current in the superconductor (i.e., excluding the current shared by the stabilizer) and n is the exponent of the power law. The values taken in the simulations are $E_0 = 1$ μV/cm and $n = 15$. The total Joule power density Q_{Joule} (in W/m) is then obtained as the scalar product of current and electric field:

$$Q_{Joule} = EI. \tag{4}$$

III. RESULTS AND DISCUSSION

As a measure of transient stability we have used the energy margin per unit conductor length ΔE (J/m). This is defined in
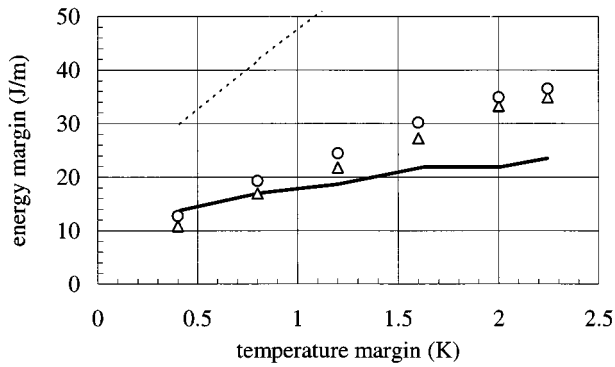
Fig. 2.   Measured (symbols) and computed (solid line) transient stability of conductor B as a function of the temperature margin, for operation at 12 kA current and 3.5 g/s massflow.
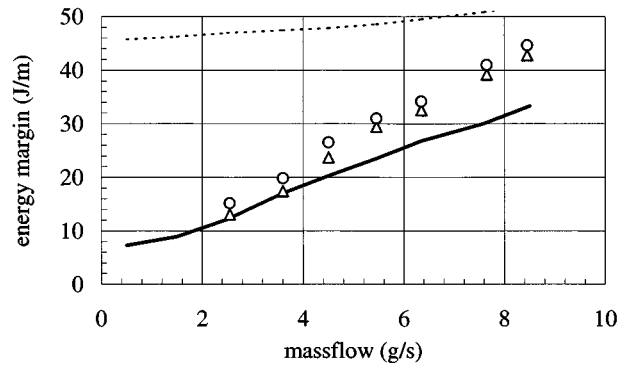

Fig. 3.   Measured (symbols) and computed (solid line) transient stability of conductor B as a function of the helium massflow, for operation at 12 kA current 1 K temperature margin.

the simulations as the integral of the power in (2), averaged between the highest value that leads to a recovery and the lowest value resulting in a thermal runaway. The experimental values used for comparison are obtained by energy calibration of the amplitudes of the two field pulses right before the quench value and producing the quench. The energy calibration was obtained using gas-flow calorimetry and is described elsewhere [3]. For comparison, we have also reported in all figures the difference of helium enthalpy between T_{op} and T_{cs} which represents an ideal upper bound for the heat absorption capability of the conductor in case of infinite heat exchange between strands and helium. All results reported here refer to the runs with background field $B_{SUL} = 9.71$ T.

A. Stability as a Function of the Operating Current

The comparison of measured and computed transient stability as a function of the operating current fraction is shown in Fig. 1 for conductors A and B respectively. The operating temperature is constant at 6.2 K in conductor A and 6.6 K in conductor B. The massflow for both conductors is 3.5 g/s. The simulation is performed in a range I_{op}/I_c from 0.4 to 1, i.e., broader than the experimental range. Taking an average value of the heat transfer coefficient of 1000 W/m²K the expected limiting current fraction for conductor A is at $I_{lim}/I_c \approx 0.9$, and $I_{lim}/I_c \approx 0.6$ for conductor B [8].

For conductor A both simulation and experiment do not show any evident drop, as expected because of the high limiting current fraction. The difference between experimental data and simulation is approximately 40% in the full range of currents. For conductor B the simulation shows a mild drop of the stability margin around the expected *limiting current*, below $I_{op}/I_c \approx 0.6$, not visible in the experimental measurements. In this case the difference between experiment and simulation is less than 5% at high current, but grows to as much as 60% at low current. In general, the simulated energy margin tends to under-estimate the measured values, in particular at low I_{op}. We attribute this result to the pessimistic assumptions taken for the transient heat transfer, as discussed later. We finally note that the simulation reproduces the experimental result in that the computed stability of conductor A (with copper fully distributed among the superconducting strands) is superior to conductor B (with segregated copper).

B. Stability as a Function of the Temperature Margin

The effect of the temperature margin ΔT was investigated in the range 0.4 K–2.3 K with operating current 12 KA and massflow 3.5 g/s. We show in Fig. 2 the results for conductor B. The simulation agrees qualitatively with the experimental results that show a linear dependence of the energy margin on the temperature margin. In this regime of operation (high operating current fraction), the measured and computed stability margin is significantly smaller than the helium enthalpy for the corresponding temperature margin. The difference between simulated and experimental ΔE is small (less than 5%) up to $\Delta T = 1$ K. At higher ΔTs the simulation underestimates the measured energy margin, with a difference of 36% at $\Delta T = 2.3$ K. The results of conductor A are similar but show a constant offset of approximately 10 J/m. Note finally that without taking into account the smooth electric field transition, i.e., with an infinite value for n, the simulation results would be affected by a 0.5 K shift that would lead to a clear disagreement with the experimental results.

C. Stability as a Function of the Helium Massflow

The effect of helium massflow is investigated operating at a current of 12 kA with a temperature margin of 1 K in both conductors, i.e., at an operating temperature of 5.53 K in conductor A and 5.95 K in conductor B. The comparison of experimental and computer results is shown in Fig. 3. The simulation broadly agrees with the experimental results, showing a linear dependence of energy margin on massflow. The difference is only few percent below 4 g/s and reaches 25% at 8 g/s. The results for conductor A show a slightly better agreement.

To explain the linear dependence we recall that higher massflow results in higher turbulence and thus an enhancement of the steady state heat transfer coefficient. The linear dependence of ΔE on massflow points to the fact that the stability in both conductors is limited by heat transfer, as discussed next.

D. Discussion

The results presented show that the experimental energy margin exceeds, sometimes significantly, the expected value, approaching the theoretical upper limit given by the helium enthalpy between operating and current sharing temperature, as would be typical for operation in the *well-cooled* regime
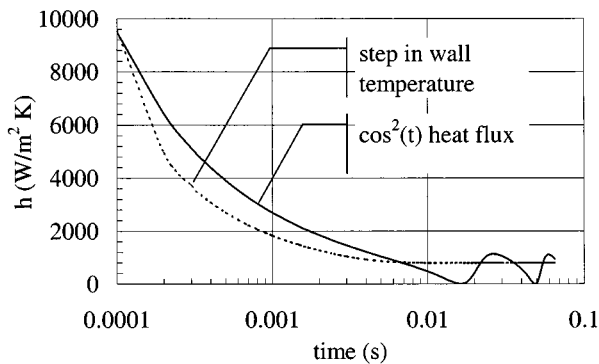
Fig. 4. Simulation of heat transfer in an ideal boundary layer with 25 μm thickness and constant thermophysical properties. The equivalent heat transfer coefficient for the boundary layer is computed analytically for a step in the strand temperature (the approximation used in Gandalf) and numerically for a time variable heat flux from the strand with a $\cos^2(t)$ dependence.

[8]. In addition the stability plots as a function of operating current fraction does not show a limiting current. On the other hand, as shown by the massflow dependence in Fig. 3, we have evidence that the stability is limited by heat transfer, as typical of the *ill-cooled* regime [8]. This apparent contradiction can be resolved considering on one hand the relatively long time of energy deposition, and on the other hand the restricted operating regime explored, limited to small temperature margin. The energy that can be transferred to the helium bath during the field pulse, proportional to the pulse duration, can be significant when compared to the available helium enthalpy, proportional to the temperature margin. This phenomenon results in the large energy margin, compared to the helium enthalpy, even in the *ill-cooled* regime, and is qualitatively reproduced by the simulation.

As anticipated, we attribute the main differences between experiment and simulation to the approximation used for the transient heat transfer coefficient h. This approximation is based on the analytical solution of the heat flux entering an ideally infinite boundary layer following a step in the strand temperature [9]. In reality, during the experiment the heat flux from the strand to the helium is a strong function of time, and thus the assumption of constant strand temperature used for the calculation of h fails. To demonstrate the influence of this effect we have performed a simulation of the temperature evolution in a helium boundary layer with constant thermophysical properties and constant thickness of 25 μm. One side of the boundary layer is bounded by the strand surface while the other side is kept at the bulk helium temperature. The equivalent heat transfer coefficient for a step in the strand temperature is compared in Fig. 4 to the heat transfer coefficient obtained for a $\cos^2(t)$ variation of the heat flux at the strand surface, simulating the heat deposition in the experiment. The difference is striking, in spite of the simplistic approach taken, and demonstrates that the approxi-

mation used may be quite far from reality. In particular the transient heat transfer can be significantly larger than what we have assumed, especially at the end of the heat pulse, when recovery takes place. Variable thermophysical properties, turbulence, the resulting changes in boundary layer thickness, and a complex geometry make a more complete analysis impractical.

IV. CONCLUSIONS

We have performed a numerical analysis of the transient stability experiment SeCRETS on two Nb$_3$Sn cable-in-conduit conductors. The numerical study of the experimental results has revealed details on the fact that the stability in the operating regime explored (low temperature margin in proximity of the normal transition) is limited by heat transfer. The stability of both samples is excellent, although the segregated stabilizer does not participate to the current sharing process. The adverse effect of copper segregation on stability is qualitatively reproduced by the simulations.

We have found that a consistent model of the voltage–current characteristic of the conductor is required to obtain accurate predictions of stability. In the case of the SeCRETS conductor the use of the power-law model described has resulted in an increase of the *effective* temperature margin by approximately 0.5 K. For design and scoping calculations the typical accuracy that can be achieved with the model described here is appropriate. We remark however that a better knowledge of the details of transient heat transfer is necessary for more accurate prediction of stability.

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