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Influence of Cable Conduction on Quench Propagation in Force-flow Cooled Conductors

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Summary

This paper discusses the influence of thermal conduction along the cable on the propagation of normal zones in force-flow cooled conductors. It is shown that because of conduction in the cable, and because of a temperature gradient between cable and cooling helium, the normal zone always propagates faster than the speed of the helium being ejected from the normal zone: the normal front advances the heated helium slug. Expressions to estimate the front advance speed are given, and its influence on the global propagation speed is discussed.

1. Introduction

The propagation of quench in force-flow cooled conductors, among them CICC's, has been subjected to intense experimental[1-3], analytical[4-6] and numerical[7-11] studies in the past 15 years, of which the references quoted above only give a limited example of the work performed. It is generally accepted that quench propagation in force-flow cooled conductors can be described to a sufficient accuracy modelling it along the conductor length (in 1-D), neglecting transverse effects. The resulting system of equations has still a remarkable complexity, so that a general analytical solution cannot be found, even in a simplified case of constant coefficients.

Because of these difficulties, all previous analytical works have concentrated into finding approximate solutions of the helium motion driven by the heating in the normal zone, and, to date, none has addressed the issues of the temperature difference between helium and conductor, and that of heat conduction along the cable length. In fact, all analytical approaches have a common assumption that conductor and helium temperature are the same. As a result, for all present analytical models the quench propagation is directly given by the expansion velocity of the heated helium bubble in the initial normal zone, with the side implication that the mass of this initial heated bubble is conserved in the expanding normal zone. This approach is only a simplification of the real behaviour, and, as will be shown here, can lead to a significant underestimate of the propagation speed when the initial normal zone is small.

The purpose of this paper is to discuss the effect of the heat diffusion along the length of the conductor on the quench propagation speed, and to give expressions to quantify this effect. In particular, known models that have been defined for propagation speed in adiabatic and bath-cooled windings are used here for force-flow cooled conductors after proper modification of the meaning of some quantities. Therefore in the next section some known results for the above conditions are reported, and will form the basis for the further discussion.

2. Preliminaries

Here we review some known results on quench propagation in adiabatic and bath-cooled windings that will be used in the next section. No derivation is reported, as details can be found in the references quoted.

2.1 Dry Conductor

We define as *dry* a conductor which is not cooled by the helium, and that therefore heats up adiabatically during a quench. This would be the case, e.g., for a force-flow conductor with an extremely poor cooling at the surface, so that the conductor temperature evolves independently on the helium temperature. The propagation speed V_{dry} for such a conductor operating at a current I_{op} and a temperature T_{op} is obviously independent on the presence of the helium, and is given by[12]:

$$V_{dry} = \frac{I_{op}}{\rho_c C_c A_c} \sqrt{\frac{\eta K}{\left(T_{cs} - T_{op}\right)}} \tag{1}$$

where the product $\rho_c C_c A_c$ is the total heat capacity of the cable, η is the stabilizer resistivity and K its conductivity (we assume that the conductivity and resistivity of the cable are dominated by the stabilizer). Note, finally, that an abrupt heating onset at T_{cs} has been assumed in (1).

2.2 Bath-Cooled Conductor

This is the case of a cable cooled by a stationary bath of helium of large heat capacity. The propagation speed in such a case is given by the following expression[12]:

$$V_{cooled} = \frac{1-2y}{\sqrt{1-y}} V_{dry} \tag{2}$$

obtained as a correction on the propagation speed in the *dry* case, with the following definition of the parameter y

$$y = \frac{phA_{cu}\left(T_{cs} - T_{op}\right)}{\eta I_{op}^2} \tag{3}$$

where now *p* and *h* are respectively the cooled perimeter and the heat transfer coefficient at the wetted surface and A_{cu} is the stabilizer cross section. From the inspection of the correction factor in Eq. (2), we note that a quench propagates only in the case $y < ½$. The relation to cryostability is evident from the definition of *y*: a cryostable conductor ($y = 1$) will never quench (provided a sufficiently large amount of coolant as a heat sink). The above expression for the propagation velocity tends correctly to that in the *dry* case at the limit of no cooling (e.g. for *p* or *h* tending to zero).

2.3 Well-cooled conductor, limited bath

What happens if the cable is well cooled (say cryostable) but the amount of helium is not infinite? Again we can find easily an expression for the quench propagation velocity in the case of a conductor whose cable is in close thermal contact (well-cooled) with helium at rest. In this case the helium and cable temperature are approximately the same, and the whole system appears from the exterior as a *dry* conductor with increased heat capacity (by the amount added by the helium). Therefore in this case we can write that the adiabatic propagation speed V_{ad} is given by:

$$V_{ad} = \frac{I_{op}}{\rho_c C_c A_c + \rho_h C_h A_h} \sqrt{\frac{\eta K}{\left(T_{cs} - T_{op}\right)}} \qquad (4)$$

an obvious modification of the propagation of the dry conductor taking into account the additional heat capacity of the helium $\rho_h C_h A_h$.

3. *Conduction Effects on Quench Propagation*

To use the previous results to evaluate the effect of conduction on the quench propagation in the cable we need to assume that the non-linearities related to the compressible and frictional helium flow can be neglected, and concentrate ourselves on the evolution of temperature. We know that the helium expands out of the initial normal zone, as heat is transferred from the cable. The expansion speed V_{he} at the end of the normal zone can be evaluated using, e.g., the expressions of Ref. [6]. The maximum speed for a given cable, operating condition and normal zone length is obtained when the pressure remains nearly constant during the expansion (i.e. the *small pressure rise* case defined in Ref. [6]), and is given by:

$$V_{he} = \frac{L_{q0} \eta I_{op}^2}{2 T_{cs} A_{cu} \rho_h C_h A_h} \qquad (5)$$

where L_{q0} is the initial normal zone length and the helium was assumed to behave as a perfect gas. Note that in Eq. (5) the expansion speed is proportional to the initial normal length. We can now distinguish two cases, depending on the expansion velocity of the helium:

1. for a <u>*short initial normal zone*</u>, the expansion velocity is small, and the induced flow is associated to a small value of the heat transfer coefficient h at the front. In this case a significant temperature gradient can build-up between conductor and helium;

2. a <u>*long initial normal zone*</u> causes a fast expansion, large h at the front and negligible temperature difference between conductor and helium.

Formally, we distinguish between the two cases in terms of the value of the parameter y defined according to Eq. (3) and evaluated at the front. In particular we define as *short* a normal zone for which the value of y at the end is below ½. If y is larger than ½ the normal zone is *long*. The reason for this usage of y will be evident in the following discussion.

We start considering a *short* initial normal zone, when the y parameter is smaller than ½ and we recall that the temperature gradient between conductor and helium at the front is significant. The conductor sees a helium bath at nearly constant temperature and the quench front propagates with the bath-cooled speed V_{cooled} defined in Eq. (2), independently on the helium flow, so that the front advance is V_{cooled} - V_{he}. The fact that the helium temperature changes slightly amounts to a negligible correction to the speed computed using Eq. (2), provided that the helium heat capacity dominates in the cable for temperatures around the current sharing point T_{cs}. Clearly, we are also assuming that the bath-cooled propagation speed is larger than the helium flow velocity. A discussion on the range of validity in the next section will show that this is always the case for typical conductors and short initial normal zones

For a *long* initial normal zone, in the case that y is larger than ½, the temperature gradient at the front is small and we can lump the cable capacity assuming that conductor and helium have the same temperature. In this condition the dominating heat transport mechanism is the convection of the heated helium slug, and we expect that the quench propagation speed is close to the helium flow velocity. In fact, a more detailed analysis shows that the additional contribution of the conductor to the total heat capacity causes the common temperature front to move at a reduced velocity V_{front} compared to the helium speed V_{he}, given by:

$$V_{front} = \frac{\rho_h C_h A_h}{\rho_h C_h A_h + \rho_c C_c A_c} V_{he} \qquad (6).$$

In a reference frame moving with the temperature front velocity given above, the homogenized system formed by helium and conductor appears as a well-cooled adiabatic conductor, whose properties have been discussed in Sect. 2.3. Hence in this moving frame the front propagates with and additional speed V_{ad} given by Eq. (4). We note finally that the factor correcting the helium velocity in Eq. (6) is generally close to unity, owing to the dominance of the helium heat capacity, and implying that $V_{front} \approx V_{he}$. Within the limits of this approximation the moving reference frame attached to the temperature front is also rigidly moving with the helium, and V_{ad} is the front advance.

With the cryterion above for the selection of the appropriate expression, we are able to estimate the front advance due to conduction in the cable. As remarked above, and discussed in the next section, for typical conductors the front will always move faster than the helium. This fact has several implications. Firstly the helium mass engulfed within the normal zone necessarily increases as the quench front advances, in contrast with the constant mass assumption often made for analytical solutions. This implies, because of the continuity balance, an increase of the massflow out of the normal zone as time proceeds. The helium speed at the front will grow in time until, provided sufficient time has elapsed, the *long* normal zone condition will be eventually met. Therefore a free-evolving quench will generally tend to the *long* normal zone case, regardless of how small the initial normal zone is.

On the other hand, a *short* initial normal zone will tend to evolve independently on the helium flow, as long as the induced flow is small. The evaluation based only on the helium flow as propagation mechanism would give in this case a significant underestimate of the actual quench propagation and accordingly conservative detection and dump times.

4. Conditions of Validity

In the case of a *short* initial normal zone, two assumptions must be met for the quench speed estimate to be valid. Firstly the heat capacity in the cable must be dominated by the helium, and secondly the helium induced flow must be smaller than the bath-cooled propagation speed. The first assumption is verified by all those copper stabilized conductors with current sharing temperature around and below the pseudocritical line of helium and with typical void fractions in the range of 20 to 50 %. In this range of values the heat capacity of the helium is approximately 1 to 2 orders of magnitude larger than that of the cable, broadly verifying the first hypothesis.

To verify the second assumption we take a typical range of force-flow cooled conductor parameters. We suppose to operate a conductor with a helium fraction of the order of 20 to 50 % of the cable cross section and copper to non-copper ratio of 1 to 2 in a range of temperatures between 4.5 and 5.5 K, with a 2 K temperature margin and overall current density between 10 and 100 A/mm^2. We compute now the corresponding range of initial normal zones L_{q0} that will give $y = ½$ using Eq. (5) for the helium velocity (with L_{q0} as a parameter), inserting the result in a standard steady state correlation for the heat transfer coefficient h and finally using Eq. (3) to determine y. With the range of conductor parameters selected above, the values obtained are of initial normal zones of the order of 5 to 15 cm, and induced helium flow velocities below 1.5 m/s. With the same parameters, the corresponding range of bath-cooled velocities is between 1 and 15 m/s, i.e. equal or well above the helium induced speed as required. Therefore, any quench initiating within this range of normal zone length or below will initially propagate in the *short* initial normal zone regime. Note that for the selection above the typical minimum propagating zone

(MPZ) [12] would be in the range of 5 mm to 8 cm length, confirming that it is physically realistic to imagine an initial propagation in the *short* initial normal zone regime.

A final remark concerns the choice of Eq. (5) for the helium expulsion velocity. As said above, that expression gives an upper limit to the helium expulsion from the normal zone, as it is based on the assumption of free expansion of a heated bubble of helium gas. No pressure build-up (through friction) is considered, which would tend to slow-down the expansion. Although a more refined analysis is possible, Eq. (5) is generally appropriate for short normal zones of the range identified above, so that no further effort has been made here.

5. An Example

We evaluate the orders of magnitude of the quench speed and of the front advance using conductor data from an experiment performed by Ando, et al. [2]. In their case an initial normal zone of 4 cm was initiated by inductively heating a cable with the characteristics reported in Tab. 1. For the range of operating conditions reported there, the initial helium induced flow, evaluated using Eq. (5) was in the range of 0.1 to 0.2 m/s, corresponding to values of the heat transfer coefficient at the front between 400 and 600 W/m^2 K. The parameter y would then assume values around 0.13-0.14 indicating that the initial quenched region was in the *short* normal zone regime (y smaller than ½).

Using then Eqs. (1), and (2) to evaluate the propagation speed (taking into account the presence of superconductor and steel in the cable cross section) we get values in the range of 10 m/s, significantly larger than the initial helium flow. Therefore initially the quench front propagated much faster than the helium expulsion. We can also compute where the transition from short to long normal zone took place, namely when the parameter y attained the value of ½. This happened when the normal zone reached about 20 cm length, i.e. within some tens of ms from the heat pulse and at a helium induced flow of the order of 0.5 to 1 m/s (according to the helium flow estimate based on Eq. (5))[†].

From this time on the front moved with a speed equal to the helium speed plus the additional amount given by Eq. (4). This last additional speed is in the range of 0.2 m/s (i.e. 20 to 40 % of the helium flow at the transition between *short* and *long* normal zone, depending on the actual operating current). The quench speed measured in the experiment ranged from ≈0.6 m/s at low current (1.6 kA) and approximately 0.8 s to ≈4 m/s at high current (2 kA) and 5 seconds, thus broadly confirming the validity of the range of estimate given for the *long* normal zone phase, as already remarked in Ref. [6] in the analysis of this same experiment. We also recall here that an increase in

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[†] Note that as the front propagates the helium velocity at the front increases, so that also the heat transfer coefficient and y increase. Thus the bath-cooled speed decreases (see the correction factor in Eq. (2)). In fact, at the time when the condition $y=½$ is met, the front speed is only equal to the helium speed plus the adiabatic V_{ad} as discussed here. This means that it is not possible to evaluate the time when the normal zone reaches a certain length simply from the initial value of the quench speed. The value given above is only an estimate.

the propagation speed is expected because of the helium engulfed through the front advance process (in addition to the change in the helium properties as the temperature increases). The recording of the initial propagation was not presented in the Ref. [2], so that here no conclusion can be drawn on the initial phase and its comparison to this analysis.

6. Conclusions

Known expressions for quench propagation in adiabatic and bath-cooled conductor have been adapted to estimate the effect of cable conduction on quench propagation in force-flow cooled conductors. It has been shown that in practical situations the quench front propagates faster than the helium, by an amount depending on the cable cooling. The front advance can be significant for short initial normal zones, for which the dominating initial propagation mechanism is in fact nearly independent on the helium flow. A cryterion for distinguishing among *short* and *long* initial normal zone has been given. An example of evaluation of the orders of magnitude has shown that the typical size of a *short* initial normal zone is of the order of some centimeters, a value comparable to the MPZ. A quench initiating over this range of length would propagate significantly faster than predicted by existing models which only rely on helium expulsion.

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List of Symbols

A_c	cable cross section [m^{2}]
A_{cu}	stabilizer cross section [m^{2}]
A_h	helium cross section [m^{2}]
C_c	cable specific heat [J Kg^{-1} K^{-1}]
C_h	helium specific heat [J Kg^{-1} K^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
I_{op}	operating current [A]
K	cable conductivity [W m^{-1} K^{-1}]
L_{q0}	initial normal length [m]
p	wetted perimeter [m]
T_{cs}	current sharing temperature [K]
T_{op}	operating temperature [K]
V_{cooled}	quench propagation velocity in a bath-cooled conductor [m s^{-1}]
V_{he}	helium expulsion velocity [m s^{-1}]
V_{dry}	quench propagation velocity in a dry, adiabatic conductor [m s^{-1}]
V_{ad}	quench propagation velocity in a well-cooled, adiabatic conductor [m s^{-1}]
y	cooling parameter [-]
η	stabilizer resistivity [Ω m]
ρ_c	cable density [Kg m^{-3}]
ρ_h	helium density [Kg m^{-3}]

Table 1. Data for the quench propagation experiment by Ando et al. [2].

Conductor geometry

Strand diameter (mm)	0.98
Number of strands	18
NbTi cross section (mm^2)	3.4
Copper cross section (mm^2)	10.2
Conduit (SS) cross section (mm^2)	25.1
Helium cross section (mm^2)	13.3
Wetted perimeter strands (mm)	55
Wetted perimeter conduit (mm)	19
Hydraulic diameter (mm)	0.69
Copper RRR (-)	60
Copper resistivity (Ωm)	6×10^{-10}
Copper thermal conductivity (W/m K)	560

Operating and critical conditions

Magnetic field (T)	7
Temperature (K)	4.2
Pressure (MPa)	1.0
Massflow (g/s)	0.0
Critical temperature (K)	6.24
Critical current (kA)	3.0
Operating currents (kA)	1.5-2.0