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This paper was prepared for submittal to the IEEE Transactions on Applied Superconductivity and the Applied Superconductivity Conference Boston, MA October 16-21, 1994

October 13, 1994
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Comparison of the Calculated and Measured Stability of a NbTi Cable-In-Conduit Conductor

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Abstract—Calculated curves of cable-in-conduit conductor energy stability margins vs. current are compared to experimental curves obtained at Oak Ridge National Laboratory for NbTi single triplex conductors. The conductors ranged in length from 1.8 m to 4.8 m, and had no imposed helium flow. The initiating heat pulse was applied for 16.7 ms over the entire conductor length.

The calculated stability curves display the large decrease in energy margin from the low current and high energy margin "well-cooled" stability region, to the high current and low energy margin "ill-cooled" region that was determined experimentally. The calculated "limiting current" of 250 A (boundary between the ill-cooled and well-cooled regions) also agrees with experiment. The multi-valued stability margins measured for lengths of 3.1 and 3.8 m could not be obtained by the computer model. Excluding the multiple stabilities, the calculated margins are generally 30% lower than the experimental values.

The decrease in energy margin in the ill-cooled region was found to be due to the low critical to operating temperature difference (2.2 K at 250 A). This prevents an initiating pulse in the ill-cooled region from being able to generate significant Joule heating without quenching, limiting the energy margin.

I. INTRODUCTION

Lue, Miller, and Dresner (Oak Ridge National Laboratory, ORNL) [1,2] made stability measurements on NbTi single triplex CICC conductors, applying the initiating heat pulse to the full conductor length using an embedded soldered heater wire. Dresner obtained analytic estimates of the limiting current [3], and for the magnitude of the thermally induced sonic waves without friction [4].

Models have been formulated that do predict multiple stabilities. In order for a model to predict multiple stabilities it must have the ability to induce turbulent flows, since laminar heat transfer coefficients are not a function of velocity (Graetz problem). Bottura and Minervini [5] developed an approximate model that uses the average induced velocity at the quench initiation region (no flow stagnation).

Their model compares favorably with the ORNL tests. Kamitani, et al. [6] developed a computer model that solves all of the basic conservation equations. They generated curves containing multiple stabilities. Possibly their large mesh size (1 m long elements with a 1 m long initial quench zone, IQ) made the multiple stability solutions possible. The CICC code [7] used in the present analysis was able to calculate multiple stabilities for the US-DPC conductor quench initiating near the inlet end [8]. The limiting current predicted by this calculation agreed with experiment. Initiation near the end of the conductor generated the necessary turbulent helium flow after the pulse for multiple stabilities. The low copper/superconductor ratio (1.17) and the low copper RRR (27) provided conditions for the existence of an ill-cooled region, even with Nb3Sn.

II. ANALYSIS

The simulations were made using computer code CICC [7], which describes the conductor using the one-dimensional energy, momentum, and mass conservation equations in the helium, and the axisymmetric conduction equations in the solid. Calculated stability curves of energy margin vs. current were compared with experimental curves from single NbTi triplex conductors obtained by Lui and Miller and presented in Fig. 6 of [2]. The conductor perimeters are listed in [1]. The tests used had a field of 7.0 T, an initial helium temperature of 4.2 K, an initial pressure of 5.0 atm, and no imposed helium flow. Conductor lengths of 1.8 m, 3.1 m, 3.8 m, and 4.8 m were considered. The heat pulse was applied to the strand over the entire conductor length for 16.7 ms.

Figs. 1-4 show the experimental and the calculated stability curves for the 1.8 m, 3.1 m, 3.8 m and 4.8 m long conductors. Generally, the calculated results are about 30% below the experimental values. However the code was not able to calculate the multiple stabilities experimentally found in the 3.1 and 3.8 m length conductors. The available cable-space enthalpy, cable-space internal energy, and conductor strand energy are also shown. The available strand energy, which contributes less than 1% to the cable-space energy, includes the energy of the heater wire and the solder attaching the heater to the strands. The energies are all integrated from 4.2 K to current sharing temperature [9]. The helium enthalpy is evaluated at a density of 140.6 kg/m³.
(4.2 K, 5 atm). These curves provide a measure of how well
the conductor uses the available helium energy.

A summary of the calculated stability curves for the four
conductor lengths is shown in Fig. 5. Since the laminar heat
transfer coefficient that exists in the stagnation region
(where the quench initiates) is not a function of velocity,
there is little difference in the calculated stability of the four
different length conductors. Small differences do develop in
the well-cooled region below the 250 A limiting current due
to differences in frictional flow resistance. The low friction
in the 1.8 m conductor allows the helium to expand in
response to the pressure generated during the pulse, making
the helium enthalpy available. At 200 A the energy margin
of the 1.8 m conductor is near the available cable-space
enthalpy, indicating efficient use of the available enthalpy.
The 4.8 m conductor has enough friction to prevent
expansion during the pulse, so only the cable-space internal
energy is available. At 200 A the energy margin of the 4.8
m conductor is near the available cable-space internal
energy, indicating efficient use of the available energy. As
the current increases above 250 A (ill-cooled region) the heat
pulses become weaker, and the generated pressures become
too weak to drive the helium expansion so the variation in
stability for the different lengths vanishes. The large
decrease in energy margin in the ill-cooled region decreases
the efficiency of the conductor to the point that only 20% of
the available internal energy is utilized.

Ref. [9] characterizes the well-cooled and ill-cooled
stability regions, and investigates the reasons why the
temperature difference, high energy margins and multiple stabilities
TPX/TF Nb₃Sn conductor stability curve does not exhibit the
large decrease in energy margin from the well-cooled to ill-
cooled regions that is exhibited by the ORNL conductor. In
summary the energy margin in the well-cooled region is high
since (in a marginal quench), the initiating heat pulse is
stronger than the Joule heating after the pulse. The margin
in the ill-cooled region is low since the initiating heat pulse
is weaker than the Joule heating after the pulse. The
limiting current occurs when the initiating heat pulse is the
same strength as the Joule heating. It was concluded that
the entire TPX/TF stability curve is well-cooled because the
large 5.8 K critical to operating temperature difference
allows the initiating heat pulse to generate a significant
amount of Joule heating, even at high currents, while
remaining stable. Being able to operate stably with Joule
heating during the heat pulse extends the well-cooled region
into the high current range that would otherwise have been
ill-cooled.

In contrast the ORNL Nb/Ti conductor has a critical to
operating temperature difference of only 2.2 K at 250 A.
This low critical to operating temperature difference does not
allow Joule heating during the pulse if the conductor is
operating much above the 250 A limiting current. Hence the
Joule heating contribution to the pulse heating can be
ignored in determining the limiting current. At 250 A in a
marginal quench, the initiating heat pulse has the same
strength as the Joule heating after the pulse (Fig. 6). In
agreement, the 250 A limiting current is at the low current
end of the ill-cooled region of the stability curve (Fig. 5).
Fig. 6 does show a significant amount of Joule heating
during the pulse; but by 275 A, there is no Joule heating
during a marginally stable pulse. Therefore the region above
250 A is ill-cooled, with the energy margin dropping an
order of magnitude from the well-cooled value.

Even with the low critical to operating temperature
difference, high energy margins and multiple stabilities
could be obtained in the ill-cooled region with a high
turbulent heat transfer coefficient. However the present
ORNL conductor model cannot generate the turbulent
convection that is necessary due to the simplifying
assumptions that the cable-space geometry, superconductor
parameters, and current are uniform in the conductor; and
that the thermodynamic parameters of the strand and the
helium vary only axially. The symmetry of this model
causes the flow stagnation region from any thermally
induced flows to remain stationary at the middle of the
conductor length. The laminar heat transfer coefficient there
(Fig. 7) is essentially only a function of time.

Since the model is symmetric and there is no imposed
velocity, only the presence of significant induced sonic
velocities could generate the helium velocities necessary for
turbulent convection. Dresner [4] analytically showed that
sonically induced flow could attain speeds of a few meters per
second. However to obtain an analytic solution, he had to
neglect friction. Figs. 8 and 9 show the sonicly induced
pressures and velocities in the middle of the conductor
length. The short 1.8 m length has the least frictional
damping. However even with this short conductor, the
velocities in the middle of the conductor length are less than
0.002 m/s, much less than the 0.1 m/s necessary to transition
to turbulent flow.

The actual conductor has a complex very non-uniform
cable-space geometry. Non-uniformities are also present in
the superconductor critical current characteristics, in the
heater characteristics, and in the current (due to local cross-
currents between strands). Also, parameter variations are
likely very three-dimensional. These nonuniformities
represent opportunities for high local turbulent cooling.

Multiple stabilities were experimentally measured [2] with
conductor lengths of 2.3 m, 3.1 m and 3.8 m, but not with
lengths of 1.8 m and 4.8 m. Initial tests were made with the
longest 4.8 m length. The presence of laminar or turbulent
cooling may offer an explanation for why multiple stabilities
occurred for some lengths and not others. The shorter
conductors were produced from the same sample by cutting
sections off of the longer conductor [2]. In tests with the
initial 4.8 m length, quench initiation occurred far enough
away from the ends for friction to suppress any turbulent
flow, so only the lower stability limit was obtained. As the
conductor was cut, regions of quench initiation could have
been exposed to the end of the conductor. The low frictional
resistance to the open end could have made it possible for a
higher energy pulse to generate the turbulent convective
cooling necessary to obtain the upper stability limit, in
manner similar to the US-DPC conductor model [8].

III. CONCLUSION

The energy margin drop in the ill-cooled region is the
result of the low critical to operating temperature difference
of the NbTi conductor. This limits the ability of the
conductor to absorb, in the ill-cooled region, a stable
initiating heat pulse that includes Joule heating. Hence the
conductor can only absorb the energy that increases its
temperature to current sharing. The higher critical
temperature of the TPX/TF Nb₃Sn conductor allows it to
operate in the well-cooled region for the entire range of
operating currents.

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Fig. 1. ORNL NbTi triplex conductor stability, 1.8 m conductor length

Fig. 2. ORNL NbTi triplex conductor stability, 3.1 m conductor length

Fig. 3. ORNL NbTi triplex conductor stability, 3.8 m conductor length
Fig. 4. ORNL NbTi triplex conductor stability, 4.8 m conductor length

Fig. 5. ORNL NbTi triplex conductor stability, calculated values

Fig. 6. ORNL NbTi triplex, heat generation at middle of conductor 250 A; 1.8 m, 16.7 ms, 120 mJ/cc heat pulse

Fig. 7. ORNL NbTi triplex, heat transfer coefficient at middle of conductor 250 A; 1.8 m, 16.7 ms, 120 mJ/cc heat pulse

Fig. 8. ORNL NbTi triplex, pressure at middle of conductor 250 A; 1.8 m, 16.7 ms, 120 mJ/cc heat pulse

Fig. 9. ORNL NbTi triplex, velocity at middle of conductor 250 A; 1.8 m, 16.7 ms, 120 mJ/cc heat pulse