Transient stability of NbTi Rutherford cables for energy storage magnet applications

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Abstract: Stability and quench behavior against transient perturbation expected during operation of a fast cycling energy storage magnet is an important issue for its design and safe operation. Understanding of thermal stability in terms of minimum quench energy (MQE) of a superconducting cable under specific operating scenario is of primary importance for its magnet application. Process of current redistribution from quench strand to adjacent strands depends on inductive coupling and has influence on quench development in the cable. The electrodynamic and thermal behavior of a ten-strand Rutherford-type cable for SMES program in the centre is studied numerically in the framework of discrete network modeling. Influence of several parameters such as uncertainties of inter-strand transverse and adjacent resistance, cooling conditions with liquid helium, etc. on MQE and quench behavior of Rutherford cable is discussed in this paper.

1. Introduction

The local disturbances is an important issue for the operation and quench protection of superconducting magnetic energy storage (SMES) magnet in spite of improvement in the manufacturing technique of multi-strand cable. The stability of a superconducting magnet against local disturbances is determined primarily by minimum quench energy (MQE)-the largest instantaneous energy deposited on the superconducting coil without the occurrence of the quench. Stability of the magnet increases with increase in MQE and therefore, MQE may be treated as the index of transient stability [1] of superconducting magnet. Stability of the superconducting Rutherford cable is described in general by a curve representing MQE as a function of transport current to critical current ratio. Stability of the cable primarily depends on [2] adjacent and cross-over resistance, electrical and thermal contact resistance, transport current distribution, mutual inductances among strands, magnetic field, average cooling area of the strand, cooling condition, etc. The critical current of the cable is less than the sum of critical currents of individual strands because of inter-strand coupling. A ten-strand non-keystoned Rutherford cable using NbTi is chosen for the SMES program at VECC [3-4]. The calculation of MQE is a complex task and requires nonlinear multi-physics analysis. The network program CUDI [5] based on electromagnetic and thermal behavior of Rutherford cable is used to simulate the stability of the cable under various operational scenarios. The primary uncertainties of the cable performance might be due to the uncertainties of cross-over and adjacent

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inter-strand resistances. The ramp rate limitation for large current capacity magnet as in transient mode operation of SMES has been a problem due to both ac loss as well as non-uniform current distribution [6]. The paper describes the MQE under various operational scenarios so that a suitable protection scheme may be envisaged accordingly. The effect of both pool boiling heat transfer and adiabatic scenario on the MQE has also been studied that provides the basis of winding details of the actual coils.

2. Cable Geometry
The superconducting Rutherford cable was produced by Luvata Waterbury Inc., USA. The strand has a 0.74 mm diameter and contains 6.7 μm NbTi filaments. The micrograph of the cable is as shown in figure 1. Because of the requirement of low transient loss during operation of SMES, Rutherford cable with inter-filamentary Cu-Mn (0.5%) matrix material is considered, which would reduce both matrix coupling losses and filament hysteresis losses in NbTi. A solder (Sn-5% Ag) coating (~0.5 μm thickness) was provided over the strand for good current redistribution among strands and to avoid any oxidation over strand surface. The cable is wrapped with 50% overlap of polyimide tape without any adhesives.

![Figure 1. Micrograph of VEC Rutherford cable](image)

The detail specification of the Rutherford conductor is summarized in Table 1.

| Parameters                      | Values       |
|---------------------------------|--------------|
| Cable cross-section (mm²)       | 1.29 × 3.67  |
| Number of strands               | 10           |
| Diameter of strand (mm)         | 0.74         |
| Number of filaments per strand  | 3900         |
| Diameter of filaments (μm)      | 6.7          |
Filament twist pitch (mm) ~15
Approximate cable lay pitch (mm) 50
Copper to superconductor ratio
In strands 2:1
Critical current \( I_c \) (A) at 5 T, 4.2 K ~4000
RRR (B=0 T) 80
Bath temperature 4.2-4.4 K

As a primary requirement to analyze the performance of the cable, the critical characteristic is measured under various background magnetic fields. At the background field of 7 T, typical critical current for samples of different spools is as shown in figure 2.

![Figure 2](image2.png)

**Figure 2.** Critical current measured at 7T background field for samples from different spools

3. Numerical calculation of MQE for different scenarios

Numerical estimation of MQE in Rutherford cable is quite complex and requires non-linear multi-physics modelling involving electromagnetic, thermal modelling. The computer code CUDI [5] developed at CERN is used to simulate the stability behaviour of Rutherford cable in VECC. In CUDI, each strand of the cable is represented by an equivalent resistance and self inductance coupled to every other strand by mutual inductance. The crossover and adjacent contact of the strands are represented by crossover \( (R_c) \) and adjacent resistance \( (R_a) \). The 3D computer code simultaneously solves the electrodynamics and thermal equations by finite difference method over a wide range of operational parameters in terms of cooling condition, magnetic field, transport current, etc. The main thermal equation that is solved in CUDI

\[
C_p(T) \frac{dT_s}{dt} V_s = P_{ext} + I_s^2 R_s + I_a^2 R_a - k_{tfc}(T)(T_s - T_{tfc})A_{tfc} - k_{ins}(T)(T_s - T_{a})A_{a} - k_s(T) \frac{dT_s}{dx} A_s
\]

Where, \( C_p(T) \) is the specific heat of the strand, \( T_s \) is strand temperature, \( V_s \) volume of the strand, \( I_s \) is the current, \( R_s \) the resistance of strand, \( k_s(T) \) is the thermal conductivity, and \( A_s \) is the cross-section of the strand, \( P_{ext} \) is the power from external pulse, \( I_a \) is the current through adjacent contact, \( T_{a} \) is the temperature of adjacent strand, \( A_a \) is the contact surface of adjacent strand, and \( dx \) is the elemental spatial step size along the direction of cable length.

The stability analysis for the evaluation of MQE has been performed considering a cable length of 1 m. The difference between the lowest energy required to quench to highest energy for recovery is within 2.5 % of energy calculated for most of the cases. The values of thermal contact resistances and
electrical resistances are considered to be uniform in space along the length of the cable. The critical current of the custom-made cable is measured at various background magnetic fields and can be expressed as

\[ i_C(B,T) = (C_1 + C_2 B) \times \left(1 - \frac{T}{T_{CB}}\right) \]  

(2a)

Where, \( C_1 = 1652.7 \text{ A}, C_2 = -132.5 \text{ A/T}, \) \( T_{CB} \) is the current sharing temperature given by

\[ T_{CB}(B) = 9.2 \left(1 - \frac{B}{14.5}\right)^{0.59} \]  

(2b)

3.1 Influence of RRR on MQE
The resistivity of matrix material copper is varied to study their influence on stability. It is that when the reduced current, \( i/i_c \) is less than 0.65, the current redistribution among the strands improves the stability (lower part of the kink region). After the reduced current \( (i/i_c) \) crosses 0.7, the current redistribution does not effectively improve the stability as shown in figure 3.

Figure 3. Calculated MQE vs reduced current for various purity of matrix material

Figure 4. Dependence of MQE on RRR (the purity of the matrix)
Operation of the SMES coil with reduced current ratio of nearly 0.7 at 7T peak field at coil would require RRR better than 70. Although higher value of RRR is beneficial at higher reduced current ratio (> 0.7) as is obvious from figure 4, but not so important in case of operation at lower reduced current ratio.

3.1 Dependence of MQE on magnet cooling conditions
The cooling of the SMES magnet coil is dominated by heat transfer to liquid helium and heat conduction as well. Liquid helium can transiently absorb the energy by an amount of tens to hundreds times greater than the enthalpy of the superconducting cable. Therefore, it is more effective from the viewpoint of enthalpy stabilization. In calculation of the MQE, heat transfer to a liquid helium coolant may influence largely the results obtained. As is well known, however, the heat transfer is quite complicated due to the effects such as nucleate boiling, film boiling, surface condition, cooling channel and transient cooling, etc. Nevertheless, the information on the heat transfer to the coolant can be obtained from the measurements of propagation velocity of normal zones in a magnet winding.

![Figure 5. Variation of MQE with operating current under different cooling scenarios](image)

However, MQE can be determined quite reasonably over the wide range of heat transfer coefficients. It is quite obvious from figure 5 that MQE in bath cooling scenario is about orders of magnitude higher with respect to adiabatic case (h=0). This is due to the fact that the overall heat capacity of the cable increases by around two orders of magnitude in case of bath cooling with respect to adiabatic scenario due to presence of liquid helium. Therefore, it would probably be a better choice to operate the magnet at bath cooling scenario as far as stability is concerned.

3.2 Influence of magnetic field transients on MQE
It is well known that operation at higher magnetic field will reduce the critical current and consequently the stability margin in terms of MQE as shown in figure 6. The inter-strand and intra-strand coupling current induces in case of magnetic field transients. The stability of the strand reduces due to simultaneous increase of total current composed of both transport current and shielding or coupling current and thus reducing the stability margin. Further, increase of strand temperature due to ac loss becomes another reason for the reduction of stability margin. The transient stability of a cable becomes worse compared to steady-state operation as shown in figure 7 due to both hysteresis loss in filaments and inter-filamentary coupling current. Therefore, it is important to keep stability margin of a SMES system considering maximum field transient during operation. The spatial distribution of magnetic field in the cable and contact resistances in the winding of the magnet during charging or discharging of SMES coil induces coupling current. The non-uniformity of strand current distributions due to inter-strand coupling affects the stability of the cable.
4. Conclusion

The stability of custom make Rutherford cable is studied using the code CUDI under different circumstances which will guide us to take up suitable measures in coil winding technique and to design suitable protection scenario. It is observed that MQE does not improve appreciably for reduced current of 0.7 or lower. Further, for lower stability margin in terms of reduced current it requires RRR of matrix material to be around 200 or more. Further, it is investigated that MQE of the cable in case of bath cooling scenario would be orders of magnitude more than that of adiabatic case. It is also been observed that for peak magnetic field of 7 T, the reduction of critical current would be less than 10% for field transient up to 2.0 T/s. However, there is need to measure the MQE under various operating scenarios so as to corroborate with the simulation results and also to have further confidence. Efforts are underway towards developing the measurement set-up of MQE under various background magnetic fields. The uncertainties of adjacent and crossover contact resistances is another major concern during simulation since there could be variation of contact resistances in actual winding over the turns. However, simulation has been carried out over a wide range of variation of contact resistances to understand its effect on stability.

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