QUENCHES AND RESULTING THERMAL AND MECHANICAL EFFECTS ON EPOXY IMPREGNATED NB_3SN HIGH FIELD MAGNETS

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Abstract

Thermal deformation and resulting mechanical stress due to quenches inside epoxy-impregnated Nb_3Sn high field magnets are studied with a combination of a quench simulation program, and the ANSYS program. We use the geometry of the high field cosine theta type dipole magnets with one meter and 10 meter length. The turns where quenches start are heated excessively, up to 100 K to 300 K, depending on the coil length and time delay. The non-quenching turns and surrounding material are not heated substantially. This large temperature gradient causes high local stress in the quenching conductors and their insulation material. The ANSYS program is used to calculate this response.

1 INTRODUCTION

The next generation of accelerator/collider projects will require the development of high field accelerator dipole magnets, with central fields in excess of 10 Tesla, using Nb_3Sn superconductor. Since energy extraction becomes difficult as the size of a magnet grows, stored energy must be dissipated inside the magnet coil when it quenches. This problem becomes greater as magnet length increases, as has been shown in our previous paper [1].

Each LHC magnet is provided with a high current diode for dissipating an individual magnet's stored energy into its own cold mass for quench protection. It is reported the hot spot temperature is on the order of 320 K to 350 K, in the event of quenches with full energy deposit [2]. The Rutherford cable of the LHC magnet is made of NbTi superconducting strands, and wrapped with Kapton and glass tapes, and not epoxy impregnated. Therefore the individual cabled conductor or individual conductor block is free to expand to some extent during a quench. After the quench, as the conductor cools, the cable will return to its original position.

Nb_3Sn strand, however, becomes brittle after the reaction phase of its manufacture. Therefore a coil wound with Nb_3Sn Rutherford cable has to be completely epoxy impregnated to keep the conductor rigid. The coil is epoxy impregnated together with spacing wedges and other material. When the superconductor quenches, it is rapidly heated, but because of the low heat conduction and brief time scale, the surrounding material will not be heated effectively except by eddy currents caused by the rapidly changing magnetic field.

In this paper we study the thermal deformation and resultant mechanical stresses in the epoxy-impregnated Nb_3Sn conductor and surrounding insulation material.

2 ANSYS CALCULATIONS BEFORE AND AFTER QUENCH

In this paper we study the thermal effects due to the quench, using the geometry of the dipole magnet with cosine theta coil, which is being developed at Fermilab [3]. A previous ANSYS analysis has been reported, covering structural analysis at room temperature and at liquid Helium temperature, and mechanical stress analysis due to Lorenz forces at the operating temperature [4].

During a quench, electrical and thermal effects occur simultaneously. However, because the electrical changes occur much more quickly than the thermal changes, we assume in this paper that the thermal effects due to a quench can be handled independently to a good approximation.

For the ANSYS analysis of post-quench thermal deformation, we use detailed meshes around the conductor area, separating insulation layers from the conductors to study the characteristics in detail.

3 THERMAL CALCULATION OF HEATER'S DELAY TIME

The heaters are installed on the outside surface of the outer layer of the coil, and can be triggered with a variable time delay. The time delay for starting a quench, after heaters are turned on, is estimated by the ANSYS analysis at 15 ms for our geometry with 10 mm wide heater strips producing 100 W/cm^2.

4 KUENCH CALCULATION

Quench processes are simulated by "Kuench 1.6" [5]. In the simulation, a magnet coil is modeled based on a long cable. This long cable is divided into elements. Heat balance equations for each element are used to calculate voltage and temperature in the element, and the circuit equation is used to calculate current. Cooling and thermal contact between turns and layers are also considered. To mimic the transverse heat transmission, thermal contacts between elements with a certain distance (length of one turn) are taken in account. Figure 1 shows the calculation model and Figure 2 shows the flow chart. Details of the simulation are described in a companion paper [5].

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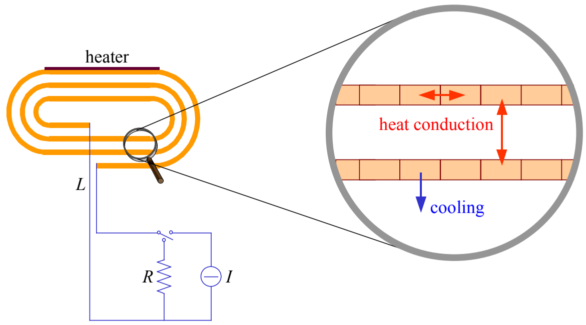

Figure 1: Quench Calculation model.

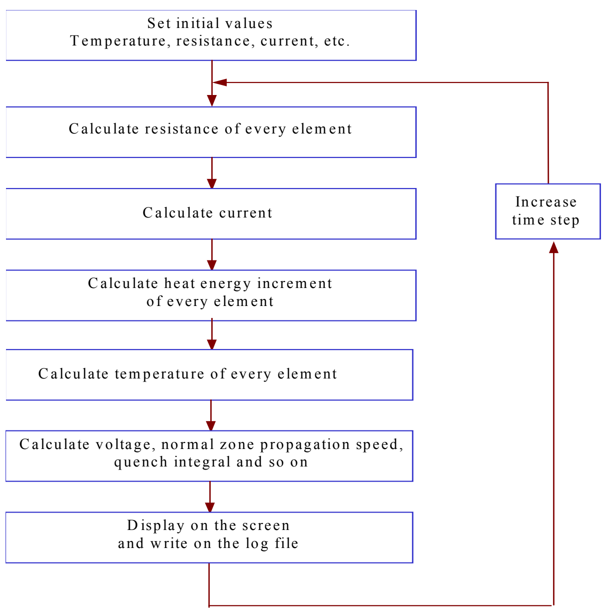

Figure 2: Flow chart of the calculation.

5 THERMAL CALCULATION BY ANSYS

The energy generated in every conductor turn is calculated by the Kuench simulation every millisecond, and its data file is input to the ANSYS program to calculate the temperature every ms in every turn.

With this information, the temperature distribution in the two-dimensional magnet cross section is studied for different magnet configurations. First, a one meter model magnet with a 30 mΩ dump resistor is analyzed; then a 10 meter long magnet with the same cross section and the same dump resistor is considered.

The temperature rise with time was animated using the ANSYS results, and it appears that the calculated two-dimensional temperature distributions in the magnet cross sections are consistent with an intuitive understanding of quench propagation. The quenching conductor cables are heated far more than the surrounding material and non-quenching conductors. This animation allows the visual confirmation of heat transfer characteristics in a cross section.

In a one meter magnet with a dump resistor of 30 mΩ, typically only the quench starting cable and its neighbor cables are heated to 100 K, without a strong effect from the heaters. With a 10 meter magnet, heaters cause most of the conductor blocks to quench. In this case, temperatures in the quench initiating cables rise to 240 K to 250 K in 100 ms, and the other conductor blocks rise to 150 K.

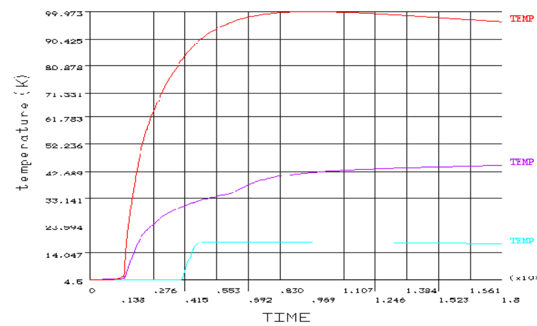

Fig. 3: Temperature variation in time at the quenching conductor and at the adjoining one of one meter magnet.

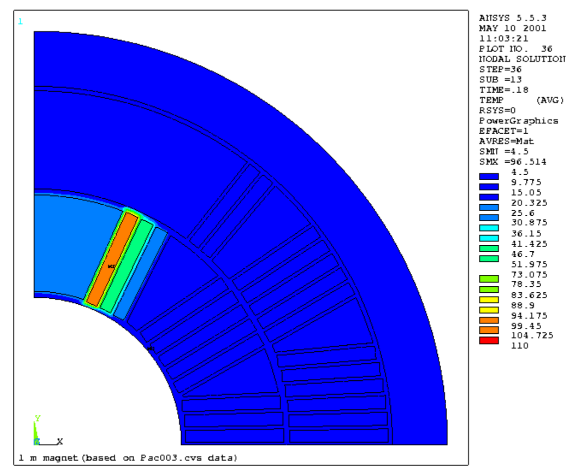

Fig. 4: Temperature distribution in the cross section of a 1 m long magnet after 180 ms.

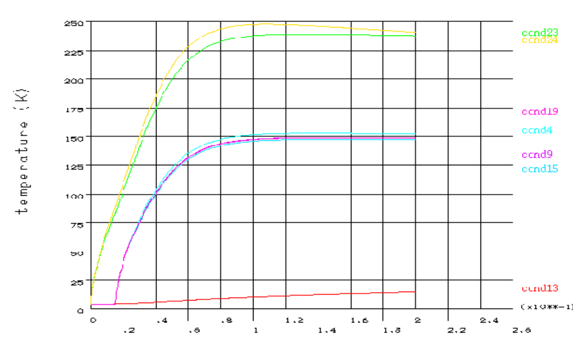

Fig. 5: Temperature variation in time at the quenching conductor and at the other conductors of ten meter magnet.

6 MECHANICAL STRESS ANALYSIS AND ITS INTERPRETATION

The quenched conductor is locally heated to between 100 K and 300 K, depending on the condition, while the surrounding material remains at low temperature. In the

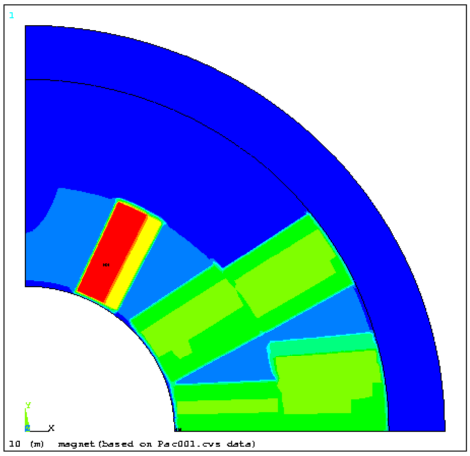

Fig. 6: Temperature distribution in the cross section of a 10m long magnet after 200 ms.

2-dimensional magnet cross section this will cause compression in all parts of the coil, especially in the heated conductors and in their wrapped insulation material. Also, this will cause shear forces to be carried through the insulation between the heated conductor and the surrounding material. This shear effect will be largest along the length of the magnet.

Shear stresses on the epoxy impregnated insulation increase with the intensity of a quench and the resulting high temperature gradients. A sufficiently violent quench can cause shear cracking between the cable and the insulation layer, and cracking in the insulation itself.

A common criterion to assess the significance of the stress level in a structure is the Von-Mises criterion. Unfortunately, this criterion does not separate the relative contribution of tension or compression and shear on the local stress level. The representation of the stress distribution using a shear versus tension-compression diagram has been proved effective for the analysis of mechanical properties in insulation [6, 7]. This approach is based on a Mohr circle representation for all the nodes of the mechanical analysis. Since the Mohr circle is defined by its radius and center, by definition located on the abscissa axis, the plot of the radius versus the center for each of the node location summarizes the whole state of stress in the material.

The center of the Mohr circle is defined as $(\sigma_I + \sigma_{II}) / 2$, σ_I and σ_{II} being the two most distant principal stresses. The radius is the point of highest shear stress and its value is $(\sigma_I - \sigma_{II}) / 2$ (assuming $\sigma_I > \sigma_{II}$). Figure 7 represents the state of stress in the conductor and insulation for the 1 meter magnet, 100 milliseconds after the start of the quench.

7 ULTIMATE PROPERTIES OF EPOXY RESIN

Recent developments of epoxy resins have proved that the intrinsic properties of these materials are far greater than what had been considered before. Among the reasons

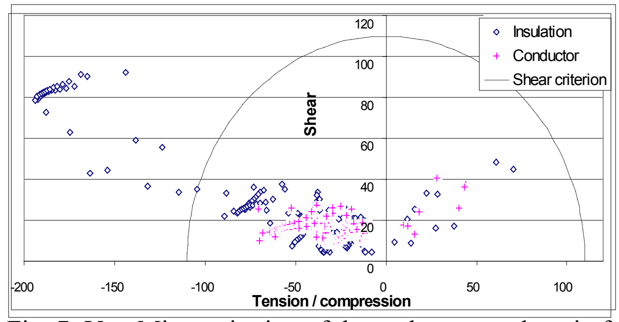

Fig. 7: Von Mises criterion of thermal stress and strain for of a 1m long magnet after 100ms.

for this progress are a better understanding of the proper design of testing samples on the one hand, and an optimization of the molecular structure on the other. Failure stresses in pure tension of up to 249 MPa has been reported, with shear failure reaching 110 MPa. These values come from different sources, and are in good agreement, because shear failures are typically expected at half the stress of tensile failures. A failure envelope for a pure shear sample of the epoxy resin is overlaid on Figure 7 using these published data. Some points of the graph are clearly outside of the failure envelope, indicating that a shear compression test is needed to qualify the insulation.

8 CONCLUSIONS

A new method to estimate the thermal stress in the conductor and insulator after quench is explained. In a one meter magnet with an adequate dump resistor the stress may be acceptable, but with longer magnets, much more study is needed.

9 REFERENCES

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