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PROTECTION FOR LOW CURRENT SUPERCONDUCTING COILS
WOUND WITH INSULATED STRAND CABLE

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Abstract

The insulated strand cable concept for winding of low current superconducting coil leads to an ideal quench protection by induction coupling. A superconducting secondary loop was made within a cable of an 6.2 Henry dipole coil. When quenching occurred, current was induced in the secondary strand above the critical value. The normal strand quenched the whole cable due to good thermal contact. The secondary loop works as a heater turned on as the wire becomes normal throughout the coil. With a well spread quench, the energy dissipation density is decreased thus preventing local burnout. The mechanism is possible because of close coupling that is present in the insulated cable as in bifilar winding. For the coil tested a 12 strand cable was used, thus a favorable 11 to 1 turn ratio was obtained for the primary to secondary. The superconductor in the secondary had a lower resistance until the critical current was achieved. A theoretical explanation is described for a simplified circuit. Test on the dipole coil with four individual shells showed that the one shell protected with the induced coupling heater always had a more rapid reduction of current.

The induced coupling heater tested and explained in this paper works automatically and does not rely on mechanical or electrical devices.

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WOUND WITH INSULATED STRAND CABLE

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Summary

The insulated strand cable concept for winding of low current superconducting coil leads to an ideal quench protection by induction coupling. A superconducting secondary loop was made within a cable of an 6.2 Henry dipole coil. When quenching occurred, current was induced in the secondary strand above the critical value. The normal strand quenched the whole cable due to good thermal contact. The secondary loop works as a heater turned on as the wire becomes normal throughout the coil. With a well spread quench, the energy dissipation density is decreased thus preventing local burnout. The mechanism is possible because of close coupling that is present in the insulated cable as in bifilar winding. For the coil tested a 12 strand cable was used, thus a favorable 11 to 1 turn ratio was obtained for the primary to secondary. The superconductor in the secondary had a lower resistance until the critical current was achieved. A theoretical explanation is described for a simplified circuit. Test on the dipole coil with four individual shells showed that the one shell protected with the induced coupling heater always had a more rapid reduction of current.

Introduction

Low current superconducting coils intended for use in a beam transport dipole magnet have been built and tested.¹ Figure 2 shows one such magnet (6-SD-50 No 2) installed in the Fermilab High Intensity Laboratory. The four foot long dipole prototype magnet can reach a field strength of 4.2 Tesla at 210 amperes. It has a six-inch diameter cold bore tube.

Another four foot long coil (6-SD-50 No 3) has been built and tested to learn and improve winding techniques and quench protection. It is in this latest coil that the protection by induction coupling was first tested.

The low current configuration was achieved by winding the coil with a cable consisting of 15 electrically insulated strands which were ultimately connected in series.

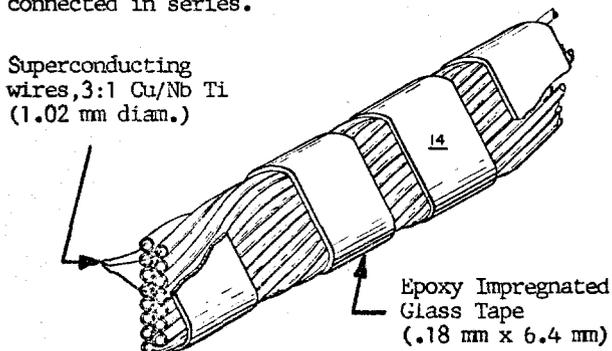


Fig. 1 Insulated Strand Cable (2.16 mm x 8.74 mm)

*Operated by Universities Research Association under Contract with the United States Department of Energy.

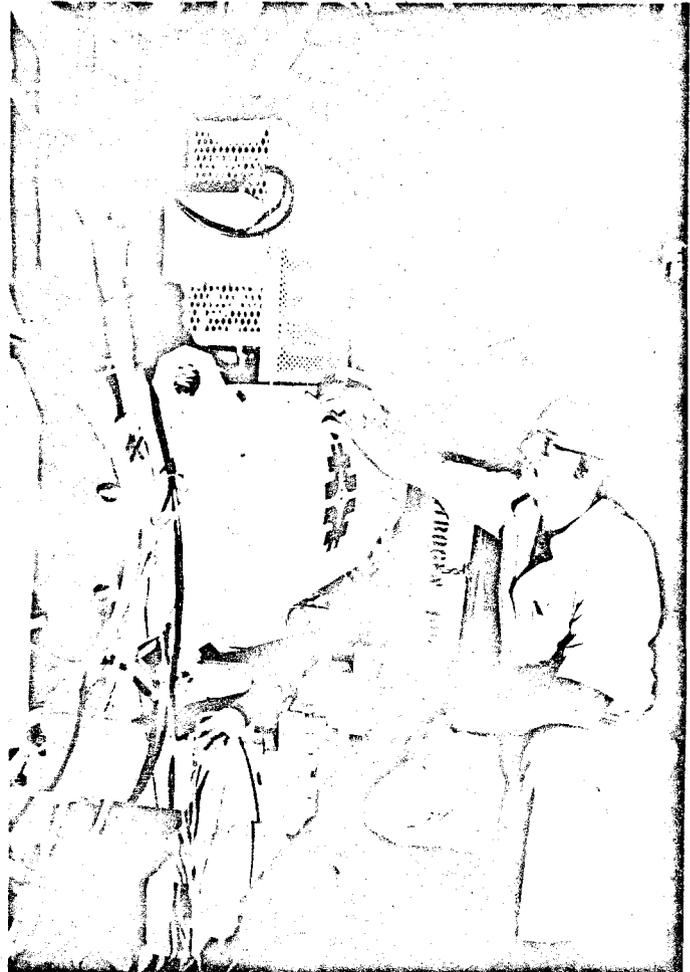


Fig. 2 Low Current Superconducting Dipole Installed in the Proton High Intensity Secondary Beam Line.

Figure 1 shows the insulated strand cable.² Each superconductor wire is insulated with a triple built of insulation (NEMA MW35). The spiral wrapped cable, after winding, produces a connecting pattern of diagonal channels. The coil composite comes out "spongy" with small voids in between conductors. The voids are filled with liquid helium which is favorable for a more cryogenic stable magnet. However, during a quench the normal propagation is slowed down due to the good cooling available. Although most of the energy is removed with the parallel resistor method, a stainless steel heater tape is also required to help spread the quench to prevent local burnout. To properly protect the coil, much electronic equipment is required. Previous tests have shown that electronic imbalance sensing devices, SCR quench switches, and heater power supplies are not always reliable. The induced coupling heater tested and explained in this paper works automatically and does not rely on mechanical or electronic devices.

Protection by Induction Coupling

Coil Tested and Results

The protection scheme is shown in Figure 3 with a simplified circuit for ease of the theoretical analysis. With the insulated strand cable, a bifilar winding is possible which gives good coupling between the primary and secondary circuits. When quenching occurs, the current I_1 begins to decrease which gives rise to a changing flux in the secondary loop. This causes a current I_2 to flow to a critical value. Tests have shown that one normal strand in the cable quenches the remaining strands due to good thermal contact.³ The secondary loop works as a heater turned on as the wire becomes normal throughout the coil. The mechanism is possible because of good coupling, lower secondary resistance (superconductor), and a favorable turn ratio of the transformer.

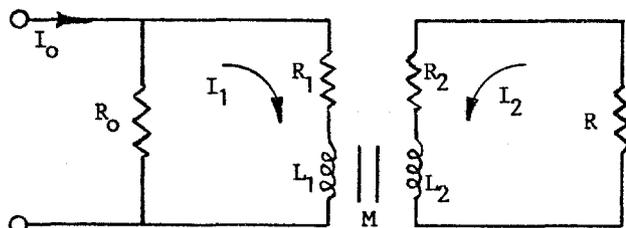


Fig. 3 Simplified Electrical Diagram of Magnet With the Induction Coupling.

The equations which describe the behavior of the circuit shown in figure 3 are as follows:

$$L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt} + (R_1 + R_0) I_1 = R_0 I_0 \quad (1)$$

$$M \frac{dI_1}{dt} + L_2 \frac{dI_2}{dt} + (R_2 + R) I_2 = 0 \quad (2)$$

M is the mutual inductance between the coil and the single strand secondary circuit. Because of the bifilar winding $M^2 = L_1 L_2$.

Before the quench

$$I_1 = I_0$$

$$R_1 = 0 \text{ (superconductor)}$$

As soon as the quench occurs R_1 jumps to a ΔR_1 value, and therefore I_1 decreases

$$I_1 = \frac{R_0 I_0}{R_0 + R_1} \quad (3)$$

From equation (2) at $t=0$, $R_2 = R = 0$ (superconductor) and because of the transformer, the current induced in the secondary is:

$$\frac{dI_2}{dt} = - \frac{N_1}{N_2} \frac{dI_1}{dt} \quad (4)$$

where N_1 and N_2 are the number of turns in the magnet coil and secondary circuits. We are interested only at the onset of the quench, because if the protection heating works, the secondary has to quench fast enough to cause other parts of the main coil to quench within 1/2 sec.

Figure 4 shows the 6-SD-50 No.3 coil ready for installation in a vertical test dewar. This coil was made similar to its predecessor¹ but with higher clamping radial force generated from the interference fit between the clamping aluminum pipe and the coil composite. The coil was tested without iron and reached 90% of the wire short critical current in 16 quenches ($I = 295$ A at theoretical end turn field of 4.7 Tesla).



Fig. 4 Low Current Coil Tested With Induction Coupling.

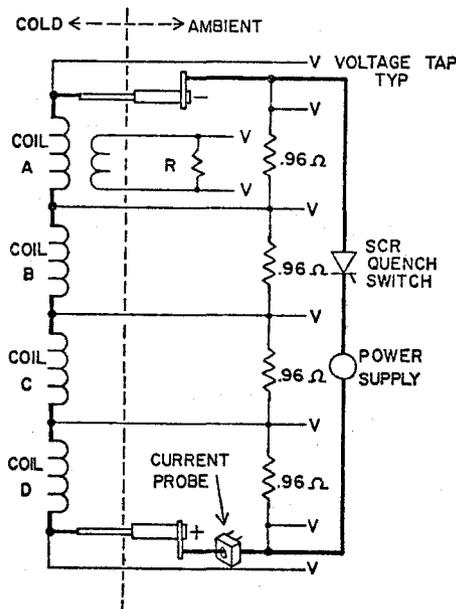


Fig. 5 Electric Diagram of Coil Tested With Secondary in Shell Coil "A" Only.

Figure 5 shows the electric diagram of the coil tested. Only the shell coil "A" had the secondary circuit built in. The cable had 11 superconducting strands electrically connected in series and one strand was used to form the secondary circuit. A shunt of 1 mΩ was placed in the circuit outside the dewar for recording the induced current I₂ as a function of time. Data was taken every 10 msec. During test No.12 we had a lead voltage trip of the power supply at 245 amp. The SCR switch opened and the current coasted down as shown in Figure 6. The secondary circuit had a resistor of 10 MΩ in series with the shunt. The voltage across each shell coil was recorded. Notice that there was no effect on coil A as compared to coil B which is opposite of the dipole midplane. Coil C&D have less number of turns than coils A&B. The resistance was too high in the secondary to induce a current.

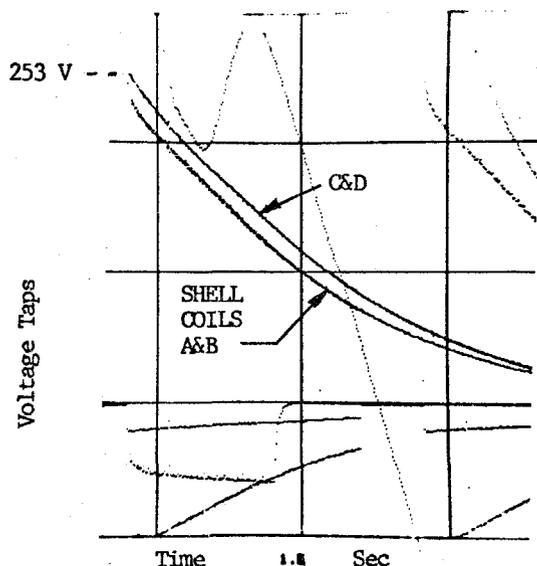


Fig. 6 Test No.12 With 245 A Coasting R = 10 M Ω no Coupling Effect

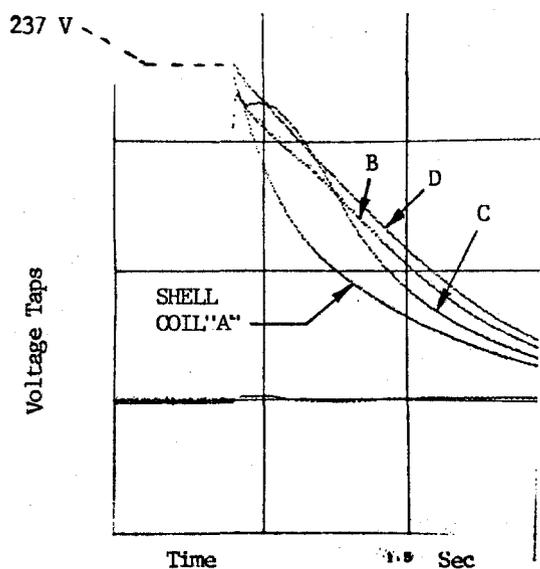


Fig. 7 Test No.22 With 250 A Coasting R = 1 mΩ (Shunt Only) Induction Coupling Quench.

In the test No.22 the secondary circuit had only the 1 mΩ shunt in the circuit. The coil was powered to 250 amp and coasted. A current of 319 amp was induced in the secondary which quenched and caused the shell "A" coil to quench also. This can be seen very clearly in Figure 7. The fast voltage decay in coil "A" shows the typical good quench propagation as seen in many previous tests. Shell coil C which is next to coil A on the same side of the dipole midplane, first started to quench from the heat, then recovered, and quenched again from more heat generated by the adjacent coil shell "A". Coil shells B&D are on the opposite side of the midplane, they were probably too far to be effected by the heat from coil A and did not quench.

Analysis

When the SCR switch opens, the current I₁ will coast with the decay I₁ = I₀ exp (-Lt/R). This is the typical expression with a resistance and inductance circuit. From test No.22 we measured:

$$\frac{d I_1}{dt} = - 295 \text{ A/sec}$$

from equation (4) of the transformer we estimate:

$$\frac{d I_2}{dt} = \frac{N_1}{N_2} \frac{d I_1}{dt} = 3245 \text{ A/sec}$$

From test No.22 we actually measured:

$$\frac{d I_2}{dt} = 8700 \text{ A/sec}$$

In the same test the secondary circuit was also effected by the other adjacent coils which can explain the discrepancy. From the measurements we estimate that the critical value of 319 amps was induced in 37 msec. The current in the secondary did not go higher which is an indication that the secondary coil quenched. As the secondary turned into a heater, shell coil "A" quenched as seen in figure 7.

The induction coupling works fast when used in conjunction with the SCR quench switch. However, we have experienced with several tests that the electronic unbalance circuitry, which causes the switch to open, does not always work.

From other coil tests⁴ we have measured the increase of the cable resistance at a quench when the SCR switch and the stainless steel heaters did not go on. An approximate ΔR₁ = 90 mΩ occurred in 1/3 second. This is a slow propagation as experienced with the insulated cable coil windings.

From equation (3):

$$\frac{d I_1}{dt} \approx \frac{-I_0}{R_0} \frac{\Delta R_1}{\Delta t}$$

and for I₀ = 250 amp and R₀ = .96 Ω

$$\frac{d I_1}{dt} \approx - 71 \text{ A/sec}$$

which yields with $\frac{N_1}{N_2} = 11$ from equation (4)

$$\frac{d I_2}{dt} \approx 781 \text{ A/sec}$$

using the required current of 319 amp from test No.22, the time required to quench the secondary would be .4 sec.

We did not run a test with a natural quench and the SCR closed to measure the effect of the secondary; however previous tests^{1,4} have shown that in several occasions the coils survived burnout possibly because of the 3:1 copper to superconductor ratio and the available liquid helium heat sink that exists in the "spongy" coil.

Conclusions

A coil is self protected when it can absorb all of its magnetic field energy internally, dissipated as heat, without any damage to the conductors. The DC low current superconducting magnet built with the insulated cable is self protected when a secondary circuit is built in. With the SCR quench switch working, the induction coupling protection works very fast, ≈ 40 msec. With failure of the SCR switch to open, it takes $\approx .4$ sec for the secondary to quench the whole coil because of the slower quench propagation. This time is longer than preferred, but tests have shown that with this type of coil construction burnouts have been avoided when electronic protection failed within this time limit. Further tests need to be made to find out the full extent of this protection by induction coupling.

Acknowledgement

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