CONF-821108--34

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DE84 004678

SHORT CIRCUIT DETECTION IN THE WINDING AND OPERATION OF SUPERCONDUCTING MAGNETS*

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Introduction

When a superconducting magnet with a shorted turn or turns is rapidly discharged, the changing magnetic flux can drive large currents through the short. These currents can lead to local temperature rises, to melting of the conductor and failure of insulation, and finally to destruction of the magnet.[1] It is, therefore, highly desirable to detect and remove shorts during the manufacture of coils.

Classification of Shorts

Three categories of shorts will be discussed: (1) shorts to the metallic bobbin or other structural elements, (2) shorts between turns caused by instrumentation wires that are deliberately connected to a turn at the end (e.g., voltage taps) and that short out to another turn but are not completely severed in the process, and (3) short circuits between turns caused by direct contact due to insulation failure by chips of metal bridging turns and by instrumentation wires that bridge turns but are severed in the process of shorting.

A short in the first category (i.e., a short to the bobbin or ground fault) will provide a complete short circuit for current only if there is a second connection to the bobbin elsewhere. For this reason, a current-limiting resistor is frequently installed in the ground connection of the center tap of the dump resistor if a center tap is used. Ground faults and weak insulation that could lead to a ground fault are readily detected with "Hi-pot" or "Megger" type equipment at an applied voltage that exceeds the dump voltage by some safety factor.

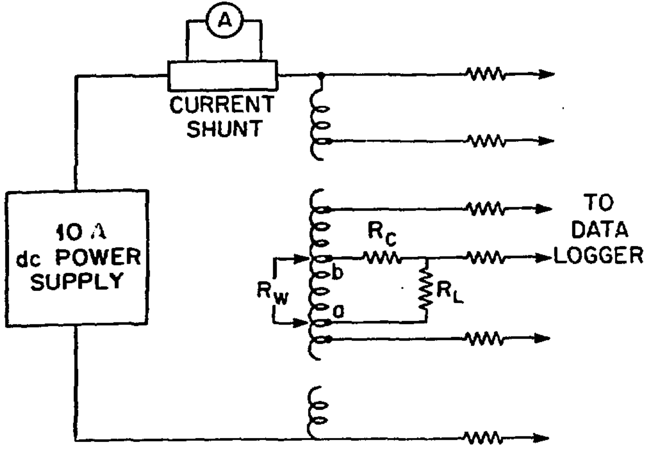

Fig. 1. Electrical schematic of the dc gradient test showing a short in a sensor lead at b. The sensor is deliberately attached to the windings at a.

Detection of Shorted Instrumentation Leads

In many experimental coils, instrumentation wires (e.g., voltage taps) are deliberately connected electrically to a particular turn and are then routed out of the windings. If such a lead is pinched by another turn, the wire insulation may fail, leading to a short circuit as shown in Fig. 1. A defect of this kind is readily detectable provided that in being pinched the wire is not completely severed and thereby open circuited and provided that the contact resistance is not too high. Shorts of the preceding type have been detected in the General Dynamics and General Electric Large Coil Program (LCP) magnets during fabrication by connecting a 10 A dc power supply across the windings and reading out the voltages on the lead wires of all sensors electrically connected to the windings. If no shorts are present, the lead wire voltages fall on a smooth curve when plotted against the number of the turn to which they are attached. If a lead wire is shorted to another turn as in Fig. 1, the voltage read by the data logger will deviate from the unshorted value by an amount dependent upon the resistance of the lead between the two points of connection to the winding, the contact resistance of the short, and the resistance of the winding between the two points of connection. Figure 2 is a plot of such data taken after the first three layers of the General Dynamics' coil had been wound. Two shorted sensor leads (denoted TI-20 and TI-25) can be identified immediately because their

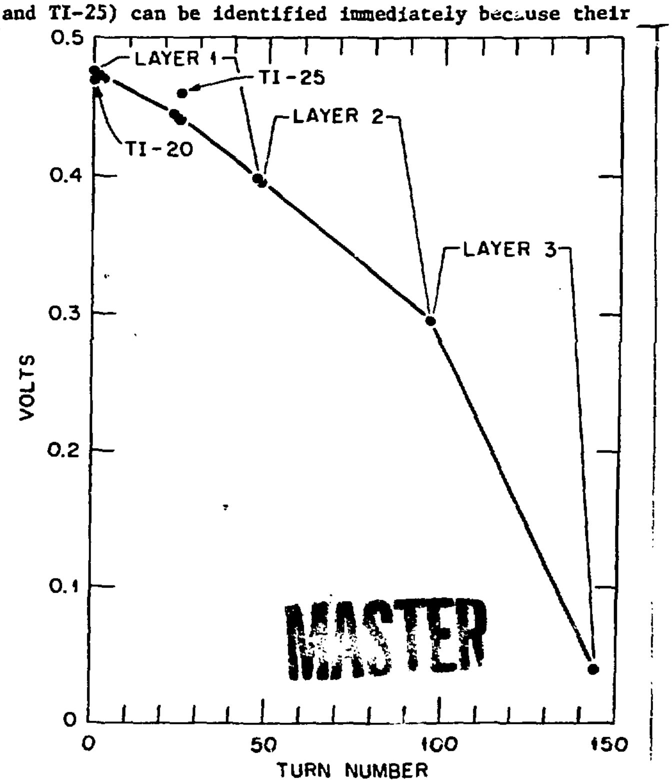

Fig. 2. Plot of sensor lead voltages vs turn number corresponding to point a in Fig. 1 for the first three layers of the General Dynamics coil

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract No. W-7405-eng-26 with the Union Carbide Corporation respective voltages are displaced from the curve. In addition, the existence of a third short can be deduced from the greater slope of the part of the curve corresponding to layer 3. The latter slope is consistent with measured single-turn resistances, whereas the slopes for layers 1 and 2 are too low. This third short was caused by the last turn in layer 2 pinching a voltage tap lead installed in the first turn of layer 1. In the process, the lead wire was completely severed, as was indicated by an infinite resistance from the end of the lead to the windings. Inspection of the portion of the curve corresponding to layer 1 also showed a slight hump due to the short in TI-25's lead wire. Even if the lead wire had been completely severed, it would have been possible to deduce the presence of the TI-25 short from the deviation of the voltages for the adjacent shorted leads together with the open circuit to the winding which would have been observed in the severed lead. Upon unwinding the three layers, the shorts were found to be exactly in the locations deduced from the measurements. Similar measurements performed on the General Electric LCP coil uncovered at least two shorts of a similar type involving leads of temperature sensors. The dc voltage gradient test thus proved to be a sensitive indicator of shorts in unsevered lead wires electrically attached to the windings and a less sensitive indicator of shorts involving severed lead wires or other conducting paths such as direct contact of turns or metal chips. In the latter case, the sensitivity depends upon the turn resistance, the number of turns spanned by the short, and the closeness to the defect of voltage taps or other lead wires which electrically contact the windings. Also, if the turn resistance varies significantly due to dimensional variations, etc., the effective sensitivity is still lower because a lower turn resistance can mimic the effect of a short in a dc test. Finally, in addition to reading out the available leads on the data logger while running a dc current through the windings, a direct scan of the voltage drops in the exposed turn can be made during winding to detect turn-to-turn shorts and shorts to the layer (or pancake) below.

AC and Pulse Methods

When the coil is in the superconducting state, dc methods cannot be used at all. Pulse and ac methods of short detection are commonly used with conventional copper magnets to detect shorts. The inductive reactance of the windings at high frequencies allows fairly high turn-to-turn voltages to be obtained.

Three basic methods are commonly used:[2] (1) the induced voltage method in which the test coil is the secondary of a split core transformer, (2) the surge or impulse method in which a high voltage capacitor is discharged across the coil terminals, and (3) a forced oscillation method in which a power oscillator drives the test coil at its self-resonant frequency. The sensitivity of all the above methods is degraded by the presence of a metallic coil bobbin, which forms a parallel shorted turn and lowers the effective coil impedance and Q of the circuit. The bobbin effect becomes important at frequencies on the order of $R_B/2\pi L_B$, where R_B is the effective bobbin resistance and L_B the effective bobbin inductance, treating the bobbin as a single lumped circuit. For the LCP magnet, this frequency is on the order of 10 Hz and is nearly temperature-independent for stainless steel with its flat resistance — temperature characteristic.

One of the most likely types of short is a turn-to-turn short. It is also the most difficult to detect because it represents a small effective percent inductance change, especially in superconducting magnets that typically have much larger numbers of turns than conventional electromagnets. A turn-to-turn short is most easily detected if it is present in the last wound layer (or pancake) of a coil during winding because the individual turns are accessible (assuming they are not completely covered with insulation). The turn-to-turn short detection threshold of the dc test discussed previouly is determined by the variation of turn resistances. In the General Dynamics LCP coil, the turn resistances were about 1 milliohm and the turn resistances varied by as much as 5%. The turn-to-turn short detection threshold by the dc method was therefore about 20 milliohms. In an effort to achieve greater sensitivity, an ac test was also performed. A 1-kHz ac voltage was applied between the beginning of the next-to-last layer and the end of the just-completed layer, and the individual rms turn voltages were measured with a digital ac voltmeter. Temporary calibration shorts were created to test the method's sensitivity. Results are shown in Fig 3. Turn-to-turn shorts of resistance up to 200 milliohms were detectable. The test was also a good indicator of layer-to-layer shorts, with the sensitivity being a function of the number of turns shorted.

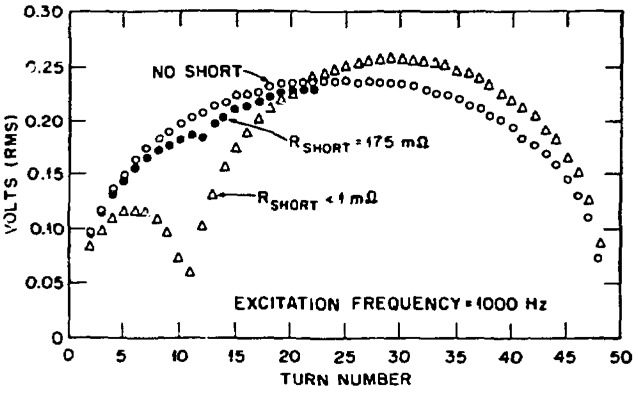

Fig 3. Data from ac short on the General Dynamics coil with deliberately created calibration shorts. Excitation frequency was 1 kHz.

Finally, phase-sensitive detection methods employing lock-in amplifiers were investigated for possible applications in future coil winding operations (Fig. 4). In these tests, two 35-turn layers of 2- by 3.5-mm rectangular cross-section dummy copper conductor with helically wound glass tape insulation were wound on a 30-cm Plexiglas former. A length of 13-mm-thick wall stainless steel pipe with an outer diameter slightly less than the Plexiglas former's inner diameter could be inserted to test the effect of the coil bobbin. The phase acceptance setting was adjusted to give zero output (90°-out-of-phase) when the voltage across the entire outer layer was input to the lock-in amplifier. The gain was then increased and the individual turn voltages of the layer were measured with this phase setting. Data taken without the stainless steel pipe agreed well with a circuit model based on inductances of rectangular cross-section, circular circuit elements representing individual turns. The model, however, did not include the eddy current effects present when the pipe was inserted. Figure 5 is a plot of data taken with the stainless steel pipe inserted. The 90° out-of-phase measurements turned out to be about ten times more sensitive than the in-phase measurements, which were nearly the same as the rms ac measurements in this case.

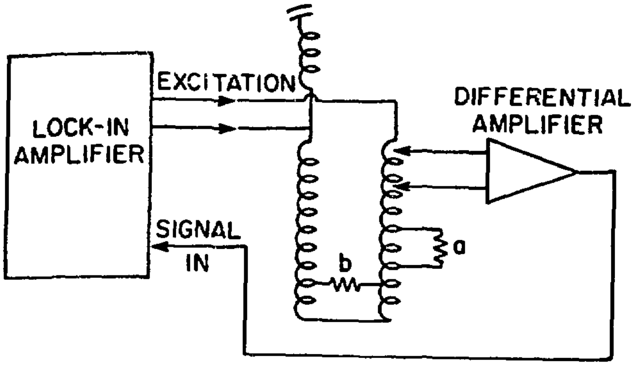

Fig. 4. Electrical schematic of a short detection test using a lock-in amplifier. The turn-to-turn short is 'a', while 'b' represents a layer-to-layer or pancake-to-pancake short.

Detection of Shorts During Coil Operation

Even if no shorts are present during winding, the electromagnetic forces present during operation could conceivably create shorts. When the coil is in the superconducting state, the zero coil resistance permits ac testing at frequencies low enough that the bobbin current effects are negligible. Shorts can thus be detected by rippling the coil current about a positive steady value at a frequency below the bobbin's inverse time constant and looking for voltages in phase with the coil current. Conceivably, digital filtering techniques could be used for highest sensitivity. The sensitivity is limited by magnetization, eddy currents, and strand coupling effects, and is improved if voltage taps are installed in every pancake or layer. If the short resistance is low enough, enough heating can occur in the short to drive the conductor normal around the short, and nonlinear behavior will occur.[3]

Short Detection with Special Coil Construction Techniques

Certain coil construction techniques make short detection much easier. If a two-in-hand pancake winding scheme is used, turn-to-turn shorts can be detected by a simple ohmmeter or Hi-pot check before the two conductors are connected in series. (The two-in-hand winding also has advantages in quench detection because the mutual inductances between the two windings and other windings are nearly the same, allowing subtraction of the inductive voltages across the two parts of the windings. This feature is being used in quench detection for the Euratom LCP coil.) Another construction technique that simplifies short detection is to wind individual pancakes on a nonmetallic or split former, which allows use of impulse and resonance methods for short detection without the damping effect of the bobbin. After testing for shorts, the pancakes are removed from the former and assembled on the permanent bobbin.

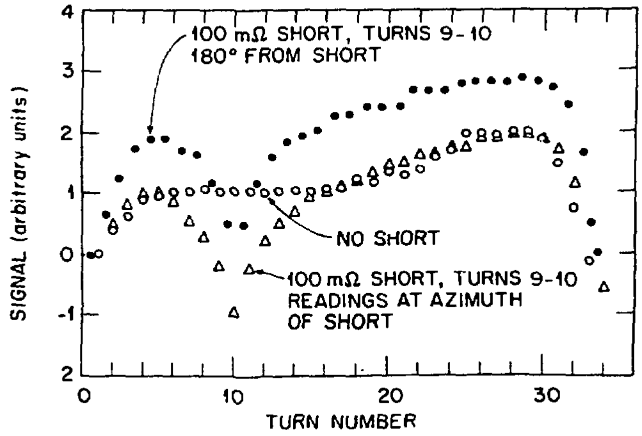

Fig. 5. Results of an ac turn-to-turn short test on the dummy winding using a lock-in amplifier at 2000 Hz. The stainless steel pipe simulating the bobbin was in place for these measurements.

Conclusions

Shorts in instrument leads attached at the sensor end to the windings that do not completely sever the lead are most easily detected by a dc voltage gradient test. The dc gradient test can also be used to detect internal shorts caused by severed leads or direct turn-to-turn contact, metal chips, etc. Greater sensitivity can be achieved by use of ac techniques, although the sensitivity is degraded by the presence of the metallic bobbin. Certain construction techniques greatly simplify short detection, and this fact should be weighed heavily in selecting a coil design and fabrication procedure.

Acknowledgments

The author is indebted to A. Gordon of General Dynamics Convair Division for providing the ac test data on the General Dynamics coil and to H. DeArmond and D. James of Y-12 Maintenance for preparing the dummy winding for the phase-sensitive ac short test.

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