Paper BY-02

International Cryogenic Materials Conference
Los Angeles, California, 24-28 July 1989
to be published in: Advances in Cryogenic Engineering Materials, Volume 36A p. 43-50

INTEGRITY TESTS FOR HIGH-T_c AND CONVENTIONAL CRITICAL-CURRENT MEASUREMENT SYSTEMS*

L. F. Goodrich and S. L. Bray

Electromagnetic Technology Division
National Institute of Standards and Technology
Boulder, Colorado 80303

ABSTRACT

Critical-current measurement systems must be extremely sensitive to the small differential voltage that is present across the test specimen as it changes from the zero resistance state to the flux-flow resistance state. Consequently, these measurement systems are also sensitive to interfering voltages. Such voltages can be caused by ground loops and by common mode voltages. Specific methods for testing the sensitivity of critical-current measurement systems and for detecting the presence of interfering voltages are discussed. These include a simple procedure that simulates the zero resistance state and the use of an electronic circuit that simulates the flux-flow resistance state.

INTRODUCTION

The determination of a superconductor's critical current (I_c) requires the measurement of extremely low voltages,[1] on the order of 1 μV. Consequently, the I_c measurement system must be quite sensitive to the resistive voltage that appears as the test specimen changes from the superconducting to the normal state, and be insensitive to other sources of voltage that might otherwise corrupt the measurement. The I_c measurement system is susceptible to sources of interfering voltage that might be negligible for many other measurements. Ground loop and common mode voltages[2] are prime examples of these sources of interference.

Because of the nebulous character of these voltages, it is often difficult to predict, based simply on the design of the measurement system, whether or not the system is prone to these problems. However, some practical test methods that are useful for checking the sensitivity and accuracy of the measurement system and for detecting the presence of interfering voltages have been developed. The test methods do not directly indicate the sources of problems; they simply indicate their presence. Consequently, the solution of these measurement problems depends on knowledge of their likely sources. As a diagnostic tool, these tests are best used for evaluating the success of specific changes that are intended to alleviate these problems.

There are two general test methods, the zero resistance test and the finite resistance test. The zero resistance test is used to detect the presence of interfering voltages, and the finite resistance test is used to evaluate the sensitivity and accuracy of the measurement system. Both tests can be conducted at either room or cryogenic temperature. The room temperature tests are usually more convenient, but less definitive because they do not depict the actual measurement conditions as precisely as the cryogenic tests.

Finally, the development of an I_c measurement system is complicated by the expensive and volatile nature of the liquid cryogen. This is particularly true when the cryogen is helium and the measurement system is computer controlled. During the first I_c measurements for a new or modified measurement system, large quantities of liquid helium are often expended during the inevitable debugging process. To address this problem, a simple electronic circuit that simulates the voltage-current (V-I) characteristic of a superconductor has been developed and tested. The simulator is an effective tool for developing the measurement system to a high level, before expending liquid helium. Also, for complex I_c measurement systems, the simulator has proven useful as part of a pre-operation check. In this way, problems can be detected and corrected prior to transferring liquid cryogen from the storage Dewar to the measurement system cryostat.

TEST METHODS

Finite Resistance Test

The finite resistance test is simply a four-wire resistance measurement where the superconductor specimen is replaced in the measurement system by an appropriate copper conductor. The idea is to measure a specimen that has a known resistance to assess the accuracy and sensitivity of the measurement system. In order to closely approximate the actual measurement conditions, it is important for the copper specimen's resistance, over the length that is spanned by the voltage taps, to be similar to that of the superconductor at its critical current. This allows testing of the measurement system at an appropriate voltage and current.

Zero Resistance Test

Interfering voltages are often difficult to detect because they are not always easily distinguished from actual specimen voltages. For example, the interfering voltages can have the character of a current-transfer voltage[3] or even a flux-flow voltage. This is particularly true of the high-transition-temperature (high-T_c) superconductors because their V-I characteristics are not as well understood as those of the conventional, or low-T_c, materials. The zero resistance test effectively simulates an ideal superconductor where the V-I characteristic is $V(I) = 0$.

Ideally, the test is carried out with the measurement system configured exactly as it would be for an I_c measurement, with one exception: the voltage tap leads are not both connected to the superconductor specimen. Rather, one of the leads is connected to the specimen and the second lead is connected to the first lead close to, but not in direct contact with, the specimen. This forms a null voltage tap pair (see Fig. 1). There are situations where the null voltage tap pair should have enhanced inductance to simulate the inductance of the differential voltage tap pair.[4] In this configuration the measured voltage should be equal to zero regardless of the current carried by the specimen. Any voltage that is detected, as the current is cycled, is an interfering voltage. The important point is that all of the electrical current paths that are present for an I_c measurement

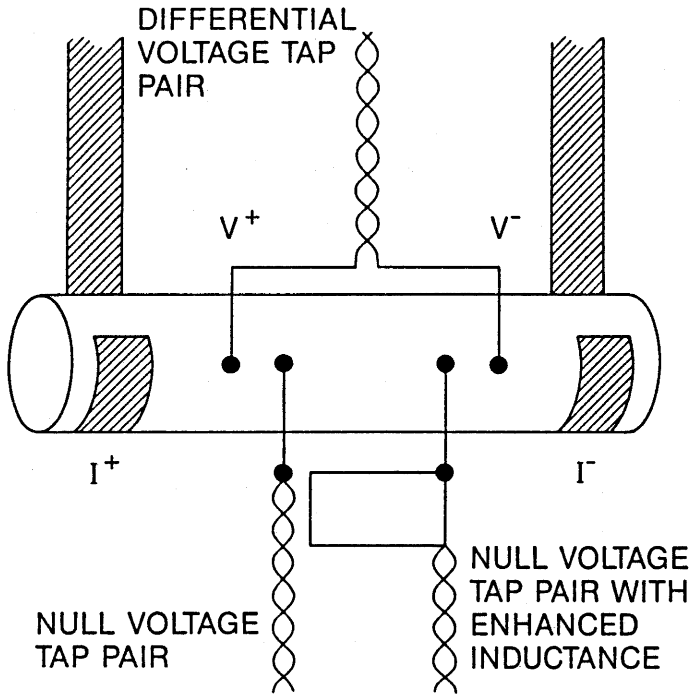

Fig. 1. Illustration of sample and lead configuration for zero and finite resistance tests.

are preserved in this configuration and the common mode voltage applied to the input terminals of the voltmeter is also the same. The only difference is that the differential voltage has been eliminated to allow easy recognition of any interfering voltages.

If the current is increased from zero to some maximum value and then decreased back to zero with a linear current ramp, equal and opposite inductive voltages will be generated for increasing and decreasing current. These voltages are easily recognized because they are of constant magnitude. In the case of a continuous data acquisition system, where the specimen voltage is recorded while the current is being continuously increased, the inductive voltages can be reduced by tightly twisting the voltage leads, but they cannot be eliminated. However, the inductive voltage is just a dc offset and, thus, it does not affect the determination of the I_c. For discrete measurement systems, where the voltage data are acquired with the current held constant at selected set points, inductive voltages are not a factor. Like inductive voltages, thermal electric voltages are always present and, if they are held constant during the data acquisition cycle, do not affect the I_c measurement.

The interfering voltages that present a problem for I_c measurements are those that change with changing current. These are the ground loop and common mode voltages. The zero resistance test is effective for detecting the presence of these voltages.

A more convenient, but less definitive, zero resistance test can be made at room temperature using a copper conductor, as in the finite resistance test. Once again, the voltage tap leads must be connected together and then connected to a single tap to eliminate the differential voltage. It is still important to retain as much of the actual I_c measurement system as possible. For example, all instruments that are used during I_c measurements (chart recorders, computers, and so on) should be connected for the zero resistance test. These peripheral devices often have ground connections and are sometimes the source of interfering voltages. For some measurement systems, the test fixture and specimen are not electrically isolated from ground. When this is the case, the room temperature test should be made with the copper conductor connected to ground through an appropriate resistance.

Superconductor Simulator

A simple electronic circuit was designed to simulate the intrinsic V-I characteristic of a superconductor. This circuit was used to characterize the response of a nanovoltmeter when subjected to a highly asymmetric periodic voltage that results from passing a dc-biased ac current through a superconductor.[4] A more general application of this circuit has been to aid in the development and testing of critical-current data acquisition systems.

Another important parameter in the determination of I_c is the measurement of the n value. The parameter n is defined by the approximate intrinsic voltage-current (V-I) relationship,

$$V = V_o(I/I_o)^n,$$

where I_o is a reference I_c at a voltage criterion V_o, V is the sample voltage, I is the sample current, and n reflects the shape of the curve with typical values from 20 to 60. A higher number means a sharper transition. In the measurement of the V-I characteristic, the sensitivity of the voltmeter is the key factor. Voltage accuracy is less significant in the determination of the I_c for a sample with a high n value. For example, with $n = 30$, a voltage error of 10% translates into a 0.3% current error.

The details of the circuit design are given in Ref. 4. The input to the circuit comes from a shunt resistor connected in series with the current supply. The output current from the simulator passes through two shunt resistors, a "high output" and "low output." Typically, the nanovoltmeter being tested is connected to the low output resistor, which generates a signal in the microvolt range, and a recording instrument is connected to the high output resistor, which generates a signal that is 10^4 times as large as the low output signal. Another channel of the recording instrument is connected to the analog output of the nanovoltmeter. These two channels are then compared and the measurement system may be thus characterized under conditions similar to an I_c measurement. The simulated values of the I_c and n can be adjusted.

The simulator does not reproduce all of the possible elements of an actual superconductor's V-I characteristic. Current-transfer voltages and the complex voltage patterns associated with flux dynamics, for example, are not produced by the circuit. However, the simulator does produce the predominant element of a superconductor's V-I characteristic, its abrupt increase in voltage with increasing current. It also produces a very low and well defined output voltage. These two capabilities make the simulator very useful for the development and trouble shooting of I_c measurement systems.

EXAMPLES OF TEST RESULTS

Measurement System Details

The copper specimen used for this study was cylindrical and measured 14.6 cm in length and 8.9 cm in diameter, and it had a voltage tap separation of about 0.1 cm. All of the tests made using this specimen were conducted at room temperature. Two different I_c measurement systems were used for these tests. The details of these measurement systems are given elsewhere.[5] For both the finite resistance test and the zero resistance test, the current was steadily increased from zero to a maximum level and then steadily reduced to zero while the voltage was recorded with a digital processing oscilloscope.

Finite Resistance Measurements

Figure 2 shows the results of a finite resistance test. The hysteresis in the data is due to inductive voltage. The lower portion of the hysteresis loop is for increasing current and the upper portion is for decreasing current. The measured resistance is approximately 1.4 nΩ. Based on the diameter of the copper conductor (8.9 cm) and the voltage tap separation (0.1 cm), this implies a copper resistivity of 0.9 μΩ-cm.

The actual resistivity of the copper is probably closer to 1.7 μΩ-cm. The discrepancy is probably due, primarily, to the lack of precision in the measurement of the voltage tap separation. To allow space for soldering, the voltage taps are staggered around the circumference of the conductor. Given the relatively small tap separation and the finite size of the taps, an accurate measurement of the longitudinal separation is difficult. Another source of the discrepancy is nonuniform current distribution within

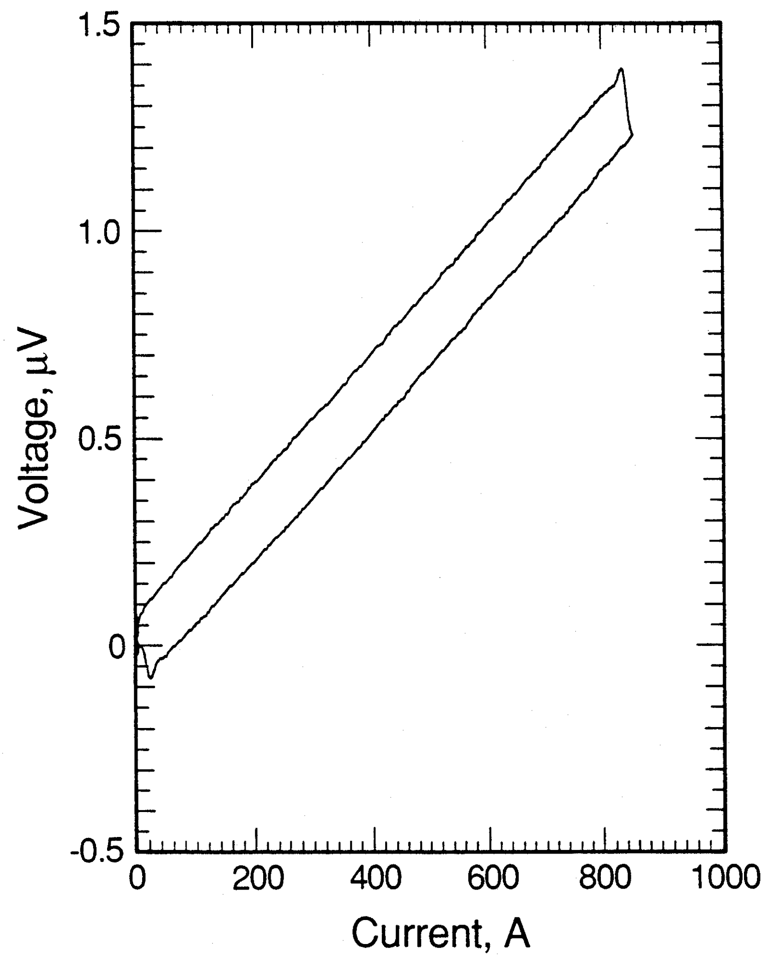

Fig. 2. Finite resistance test, voltage versus current for a copper sample.

the conductor. For an accurate resistivity measurement, the separation between either current contact and its adjacent voltage tap should be at least five times the diameter of the conductor. This allows uniform current distribution in the region of the voltage taps. For the conductor used in these tests, the separation between the current leads and voltage tap leads is less than the diameter of the conductor. Ideally, a longer conductor with a greater tap separation would be used for this test. Nonetheless, this test demonstrates the sensitivity of the measurement and, to the extent that the measured and actual values of the copper's resistivity are in the same range, the accuracy of the measurement is demonstrated.

Zero Resistance Measurements

The results of a zero resistance measurement are shown in Fig. 3. This test was made using the same measurement system that was used for the finite resistance test. The voltage scale for this plot is nanovolts. Again the hysteresis is caused by inductive voltage. The continuous curve (upper portion of the loop) is for increasing current and the discrete data are for decreasing current. The important point is that, if the inductive voltage is subtracted from the data, the measured dc voltage is essentially equal to zero. This measurement system has a voltage noise of about ±5 nV and a voltage measurement uncertainty of about ±2 nV ±2% of the signal.

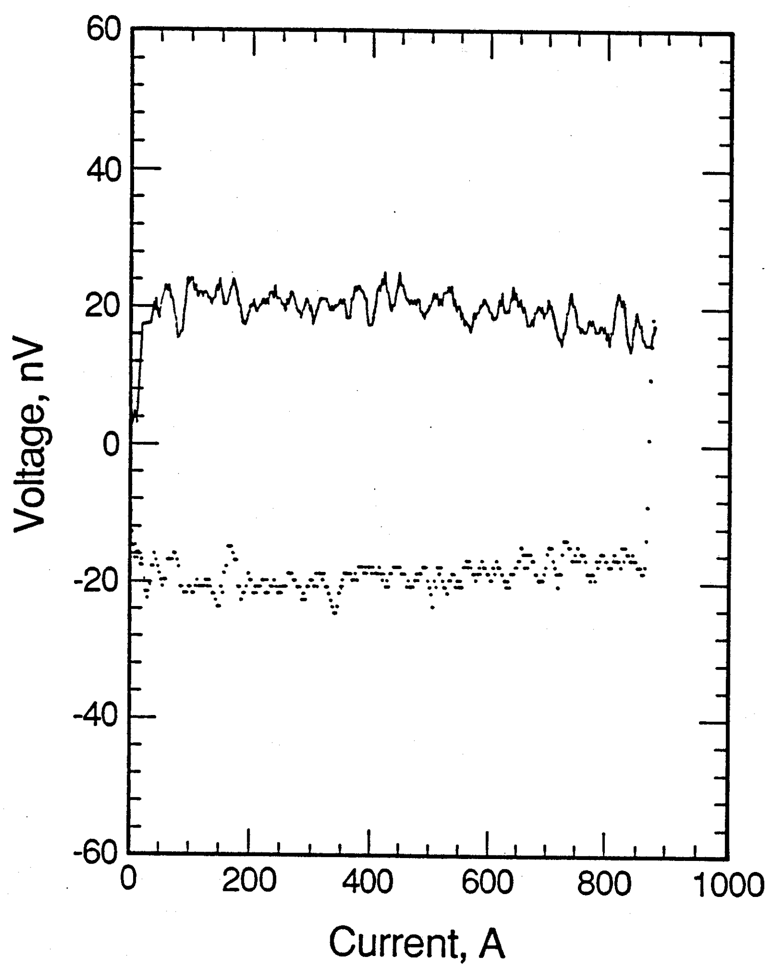

Fig. 3. Successful zero resistance test, voltage versus current for a copper sample.

In contrast, Fig. 4 shows the results of a zero resistance test for another measurement system. In this case, the voltage scale is in microvolts and, even if the inductive voltage is subtracted from the data, the measured voltage is not equal to zero. This is an example of an interfering voltage. In an actual I_c measurement, the interfering voltage would be detected along with any differential voltage, thus altering the I_c measurement. In fact, the abrupt increase in voltage that occurs at approximately 900 A might be mistaken for a superconducting transition. The features of the increasing current (continuous curve) are reproduced for the decreasing current (discrete points).

DISCUSSION

Other examples of integrity tests can be found in Ref. 5, where various combinations of voltmeters, power supplies, and load grounding conditions are given. These combinations can change the results significantly; a voltmeter that works well with one current supply may not work with another. In general, if the load can be grounded near the test sample, the level of interfering voltages can be reduced. The resistance of the voltage tap leads can also be a factor; the higher the lead resistance is, the larger the interfering voltage.

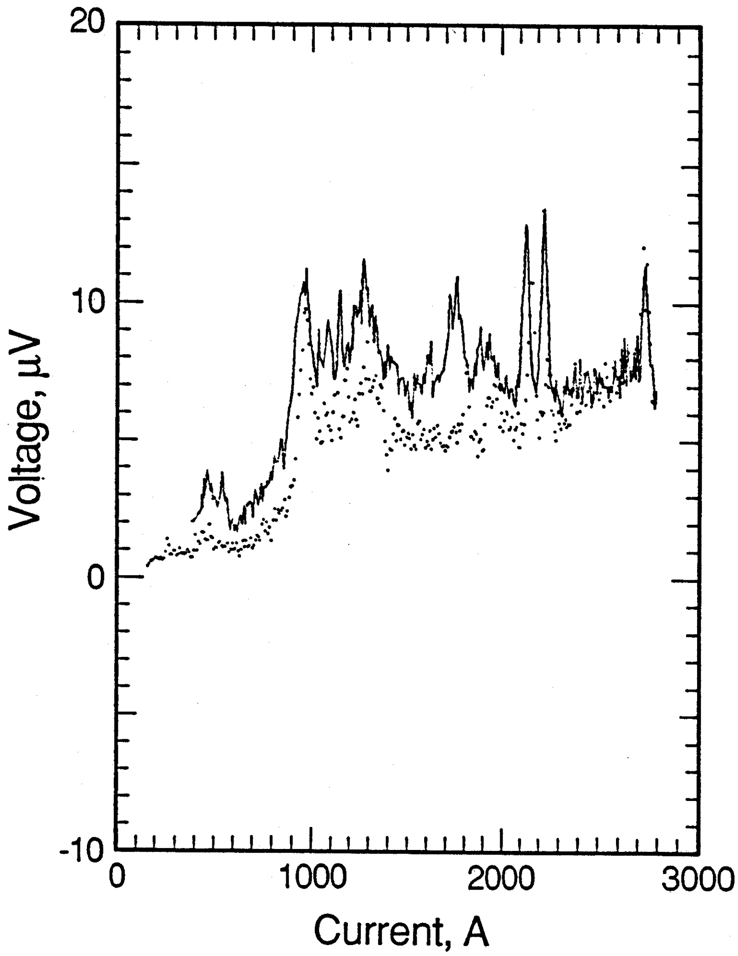

Fig. 4. Unsuccessful zero resistance test, voltage versus current for a copper sample.

The required cross sectional area of the copper test specimen used in the finite resistance test depends on the I_c of the superconductor, the selected I_c criterion, and the test temperature (room or cryogenic). For high-current systems the required size of the copper specimen can become impractical. However, low-current systems may require only a copper test specimen that is comparable in cross sectional area to that of the superconductor. The length of the copper specimen is also important to ensure an accurate measurement of its resistivity. It should be long enough, in comparison with its cross sectional area, to ensure uniform current distribution in the area of the voltage taps.

CONCLUSIONS

A set of simple procedures that will test the integrity of measurement systems used for critical-current determinations on high-T_c and conventional superconductors has been developed. These tests include a finite resistance, a zero resistance, and a superconductor voltage-current simulator. In the measurement of the critical current, voltage sensitivity is a key factor. The zero resistance test is the most effective test to detect the presence of interfering voltages such as ground loop or common-mode voltages and will determines the voltage sensitivity limit of a measurement system.

ACKNOWLEDGMENTS

The authors extend their thanks to W. P. Dube' for the idea of a zero resistance test, and to R. L. Spomer for drafting.

This work was supported by the Department of Energy, Office of Fusion Energy and Division of High Energy Physics.

REFERENCES

1. L. F. Goodrich and F. R. Fickett, Critical current measurements: a compendium of experimental results Cryogenics 22:225 (1982).
2. Ralph Morrison, "Grounding and Shielding Techniques in Instrumentation," John Wiley & Sons, New York (1977).
3. J. W. Ekin, Current transfer in multifilamentary superconductors. I. theory J. Appl. Phys. 49:3406 (1978).
4. L. F. Goodrich and S. L. Bray, Current ripple effect on superconductive d.c. critical current measurements Cryogenics 28:737 (1988).
5. L. F. Goodrich, S. L. Bray, W. P. Dube', E. S. Pittman, and A. F. Clark, "Development of Standards for Superconductors, Interim Report January-December 1985," NBSIR 87-3066, National Bureau of Standards, Boulder, Colorado (1987).