Comparing the Accuracy of Critical-Current Measurements Using the Voltage-Current Simulator

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***Abstract* - A passive voltage-current simulator developed by the National Institute of Standards and Technology (NIST) is used to compare the accuracy of critical current measurements and the power-law behavior of high temperature superconductors (HTS). In this study, critical current measurements made from four data acquisition and analysis systems are compared with those carried out at NIST. This paper also discusses various measurement techniques, methods of calculating critical current, and n-values. The V-I simulator is believed to be an advancement towards defining the standards for critical current measurements and ensuring the traceability of results at different test facilities.**

I. INTRODUCTION

The accuracy of critical current measurements made on high temperature superconductors (HTS) is influenced by cooling rate, current and voltage taps, sample mounting method, response of the power supply to inductive loading, and instrument slew rates.

The V-I simulator developed by the National Institute of Standard and Technology (NIST) is an electronic circuit which emulates the extremely nonlinear voltage current characteristic of a superconductor [1, 2]. It can be used to check the reproducibility of critical-current measurements from different test facilities. A passive (2 A / 50 A) simulator was used to compare the measurements from four measurement systems with those done at NIST.

A. Critical Current Definitions

One of the following three criteria is typically used to define critical current.

1) Electric field criterion. The critical current is that current which corresponds to a certain electric field, usually 1 μV/cm.

2) Offset criterion. In this method, the line which is tangent to the V-I curve at a specified electric field is extrapolated to zero voltage. The critical current is defined as the current at which this line crosses the zero voltage line [3].

Figure 1 illustrates the usage of these two criteria.

3) Resistivity criterion. The critical current is defined as the current at which the conductor resistivity approaches a certain value, usually 10^{-11} Ω-cm. Figure 2 shows the determination of critical current using the resistivity criterion.

B. Definition of n-value

The voltage-current (V-I) characteristic of a superconductor can often be modeled by the empirical relation:

$$V \propto I^n \quad (1)$$

The n-value (also called index) reflects the abruptness of the transition from the superconducting to normal state. Typical values of n range from 10 to 100 [4]. The n-value is computed by determining the slope of V-I curve in log-log space.

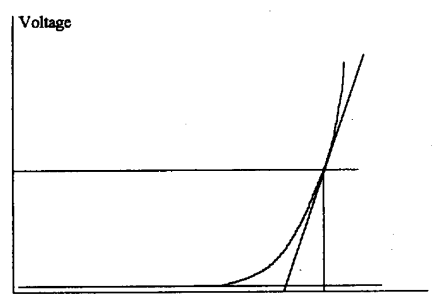

Figure 1. I_c calculation based on field criterion I_{cf} and offset criterion I_{co}.

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In addition to critical current and n-value, the *second derivative of the voltage-current curve* is also an important parameter and can be thought of as the distribution of the superconductor's critical current density [5]. The relation between n-value and first and second derivative of the V-I curve is described in Reference [6].

The n-value and I_{co} are more sensitive to the details of the analysis than I_{cf}.

I_{co} is related to I_{cf} by the following relation:

$$I_{co} = I_{cf}(1 - 1/n). \tag{2}$$

The critical current based on resistivity criterion can be approximated by the relation

$$I_{cr} = (I_{cf}^{n} (\rho/A))^{1/(n-1)}, \tag{3}$$

where ρ is the resistivity criterion and A is the conductor cross-sectional area. This relation assumes a constant value of n at both criterion and introduces a slight error. This relation has been used to calculate I_{cr} for approximately 100 HTS samples. The measured critical current was within 2% of the calculated value for most samples.

The passive simulator can emulate the electrical characteristics of a 1 cm or 100 cm long superconductor at 2 or 50 A. The n-values for both simulations are set close to 23.

II. Measurement Methods

System 1. Manual Data Recording: In this method the current was increased in steps. The voltage and current were manually recorded after a time delay of 5 s. A 100-s delay was also made before recording data for the 2-A simulation. System layout is explained in Figure 3.

System 2. X-Y Plotter: The current was controlled using a ramp generator. The current and voltage measurements were recorded using an X-Y plotter. Different ramp rates were used to see the possible effect on I_c measurement results. System layout is explained in Figure 4.

System 3. Computer Controlled Data Acquisition: The current supply was controlled with the computer. The current was increased in steps. The computer recorded the voltage and current readings. A time delay of 1 and 5 s was used before recording the data after each current increment. The computer averaged 2000 readings which were taken over a period of 200 ms. System layout is explained in Figure 5.

System 4. Computer Controlled Data Acquisition with Sensitive DC Amplifiers: The same measurement as described in System 3, except the null detector and digital multimeter (DMM) were replaced by two sensitive DC differential amplifiers.

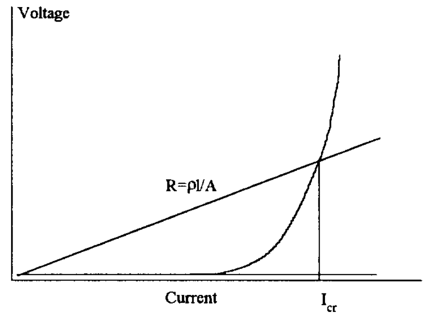

Figure 2. I_c based on resistivity criterion (I_{cr}).

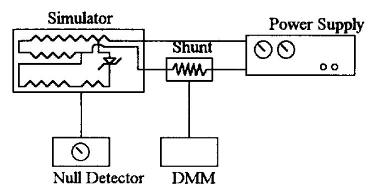

Figure 3. Critical current measurement System 1. Data recorded manually from null detector and digital multimeter.

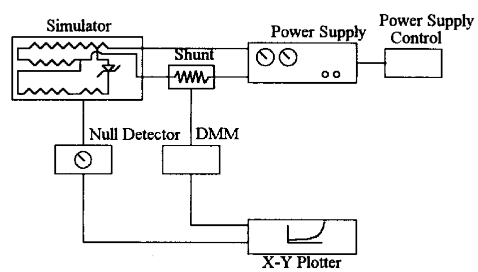

Figure 4. Critical current measurement System 2. Data recorded on the X-Y plotter.

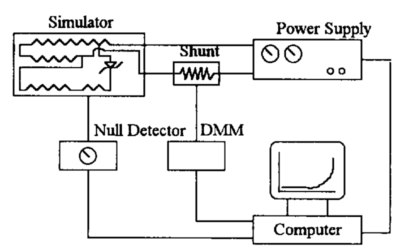

Figure 5. Critical current measurement System 3. Computer-controlled measurements.

III. Measurement Results

A. Critical Current Measurements

A typical V-I curve generated by the 2-A critical current simulator is shown in Figure 6. A summary of critical current measurements made with 100 cm long conductor simulation are presented in Table 1. Since other criteria are more sensitive to the calculation method, I_{cf} (1 μV/cm) was used to compare the results.

The difference between 5 and 100 s delay on System 1 was less than 0.06%. This system yielded the highest I_c value among the four test systems.

System 2 yielded the lowest I_c, under the most nearly optimum conditions (slowest current ramp rate). The maximum to minimum of I_c values was 0.7% for 2-A simulation and 1.1% for 50 A. If we exclude System 2, the range of data from the remaining systems is less than 0.44% for both simulations. System 2 had a range of about 1% which was the largest variation for conditions within a setup. The slew rate for the X-Y recorder and filtering may be responsible.

On System 3, the difference in I_c measured with 1 and 5 s delay was larger for 1 μV/cm criterion than for 10 μV/cm criterion and was 0.8% in one case. This may indicate that the null detector does require the longer settling time.

On System 4, the only difference between the delay times was observed on 50-A simulation and the two criterion showed opposite trends. The 0.15% is probably not significant.

Table 2 shows the comparison between the I_c measurements done at the two laboratories. The difference between I_c values is less than 0.45%. This range reduces to 0.25% if System 2 (X-Y recorder) is omitted from the calculation.

n-value Calculations

A typical n-value versus voltage curve is shown in Figure 7 for the 2 A simulator. A summary of n-values is given in Table 3. The values reported here are those corresponding to I_c values shown in Table 1.

The range of n-values determined from three systems was less than 2.5%. The difference between the average of these values and NIST values are less than 5%.

TABLE 1

Results from critical current measurements using the V-I simulator.

Simulation	2 A	50 A
NIST	1.803	45.13
System 1	1.805	45.14
System 2	1.792	45.65
System 3	1.797	44.97
System 4	1.803	44.97

TABLE 2

Comparison of critical current measurements to the NIST results.

Simulation	2 A	50 A
NIST - Avg.	-0.19 %	-0.45 %
NIST - Min.	-0.59 %	-1.97 %
NIST - Max.	-0.13 %	+0.01 %
NIST-Avg. without System 2	-0.06 %	-0.24 %

TABLE 3

Results of n-value measurements.

Simulation	2 A	50 A
NIST	23.06	23.08
System 1	22.65	22.34
System 2		
System 3	23.08	21.79
System 4	23.00	21.79

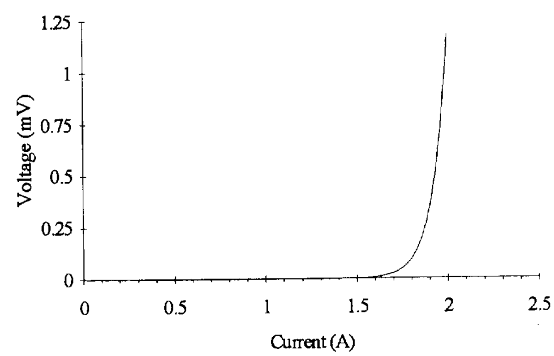

Figure 6. A typical V-I curve obtained from 2 A simulation.

IV Conclusions

Among the four critical current measurement systems analyzed, the results from X-Y recorder setup had the largest variation and difference from NIST results; however, there are advantages to an X-Y recorder system. It is simplest, easiest to observe, and shows the dynamic response of the superconductor. For the remaining three systems, the differences were less than 0.4%.

The V-I simulator developed at NIST appears to be an effective tool to ensure the reproducibility of critical current measurements and to compare the results from different test facilities. Although it is not an absolute reference for critical current measurement calibration, it can be used to determine the relative difference between test and analysis methods. The reproducibility of the results from the simulator is remarkable; over a period of four months, I_c did not change by more than 0.01%.

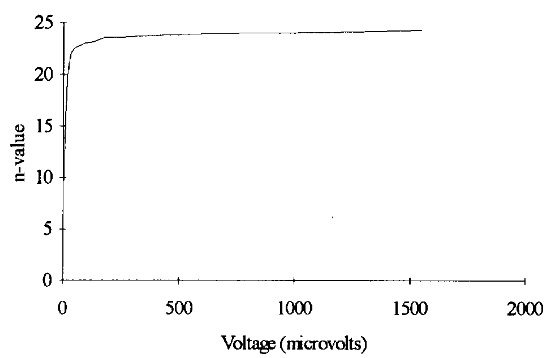

Figure 7. A typical n-value versus voltage curve obtained using the 2 A simulator.

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