Anomalous Switching Phenomenon in Critical-Current Measurements When Using Conductive Mandrels

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Abstract—NIST and other laboratories have observed an anomalous switching phenomenon that can occur in critical-current measurements of coiled Nb–Ti and Nb$_3$Sn superconductors when mounted on an electrically-conductive measurement mandrel. During acquisition of the voltage–current (V–I) characteristic, large voltage discontinuities are observed. This switching phenomenon results in a multivalued V–I curve, and apparently multiple "critical-current" values. An explanation of this phenomenon, some necessary conditions for the switching to occur, as well as methods of detecting the phenomenon are given.

I. INTRODUCTION

INACCURATE but reproducible critical-current (I_c) measurements can be caused by a number of subtle factors such as high contact resistance [1], thermal electric voltages [2], current ripple, sample motion in a magnetic field, current transfer [3], poor voltage contacts, and ground loops [4]. In this paper, we address another source of erroneous but reproducible I_c measurements. We have observed, as have other laboratories, a switching phenomenon in which a metastable state is created when a portion of the transport current bypasses the superconducting sample and flows through an electrically-conductive measurement mandrel. The switching mechanism is metastable, since it depends on the details of the voltage–current characteristic, the resistance of the conductive mandrel, sample cooling, and the position of the voltage taps relative to the current injection sites. This bypass current can yield inaccurate but reproducible critical-current measurements.

Critical-current measurements on Nb–Ti and Nb$_3$Sn wires are usually performed with a coiled sample mounted on a cylindrical mandrel to support the sample against Lorentz forces during the measurement. The mandrel can be conductive or insulating. The current contacts are usually made near the ends of the mandrel. In this configuration, the conductive mandrel is in electrical contact with each end of the sample, and with appropriate conditions, a parallel current path may be established. Although this switching phenomenon points to a disadvantage for conductive mandrels, it may be necessary to use such mandrels to control differential thermal contraction between the sample and mandrel [5].

II. EXPERIMENTAL OBSERVATIONS

This phenomenon is illustrated in Figs. 1–3. The synthesized V–I characteristics shown in Figs. 1 and 2 are representative of actual I_c measurement results on different samples at different laboratories. However, the conditions necessary to create this phenomenon are rarely achieved.

We have observed curves similar to Fig. 1 at NIST, whereas other laboratories have observed curves similar to Fig. 2. Fig. 1 illustrates a larger effect than Fig. 2; however, the cause of the anomalies is the same for both cases. We give the following explanation: a portion of the superconductor outside the voltage tap region, but inside the current contacts, goes into the normal state, resulting in a small resistance in the superconductor (see Fig. 3). This resistance in turn causes some of the current to flow through the mandrel, thus reducing the current through the superconductor. As the normal zone grows, the amount of the current bypassing the sample through the mandrel increases. Under appropriate conditions, the normal zone will stop growing if a dynamic equilibrium between the heat generated by the normal zone resistance and the cryogenic cooling is attained. If the normal zone does not continue to grow or extend into the monitored voltage tap region, little voltage will appear on the voltage taps. In fact, because the current through the sample is now lower, the measured V–I curve is shifted to the right in current, with respect to the true curve, by the amount flowing through the mandrel. Depending on the amount of current flowing through the mandrel, the voltage can drop to zero or to a lower part of the resistive transition.

Fig. 2 shows a hysteresis effect. Once the normal zone is established, the overall current has to be reduced sufficiently for the normal zone to cool and revert to the superconducting state. Until this occurs, the higher current branch of the V–I curve will be retraced.

There is a possible third case for this phenomenon in which the switch occurs before a voltage drop is measured on the center portion of the sample. This would result in a V–I curve like the one in Fig. 1, except the voltage would remain near zero in the current range from about 40 to 50 A. In this case, the measured V–I curve would not seem anomalous. The increase in voltage near 70 A would appear to indicate the I_c, however, this is just the inevitable quench that results from increasing the current to well above the true I_c. Thus it is important to have a technique to detect this phenomenon even when the V–I curves do not appear to be anomalous.
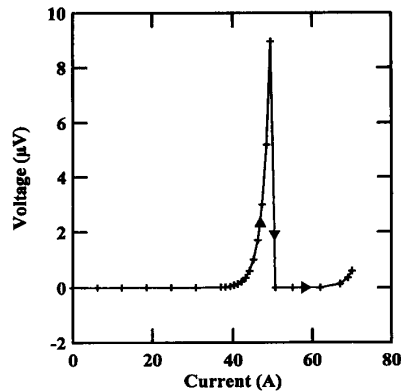
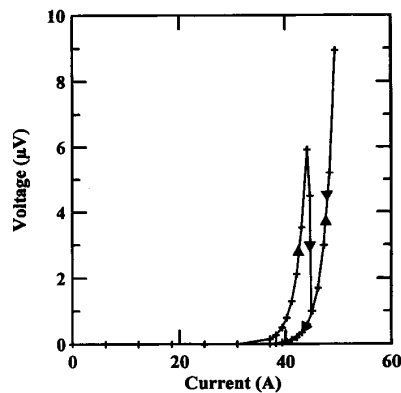Fig. 1. Synthesized $V-I$ characteristic illustrating the metastable switching phenomenon observed at NIST.

Fig. 2. Synthesized $V-I$ characteristic illustrating the metastable switching phenomenon observed at other laboratories.
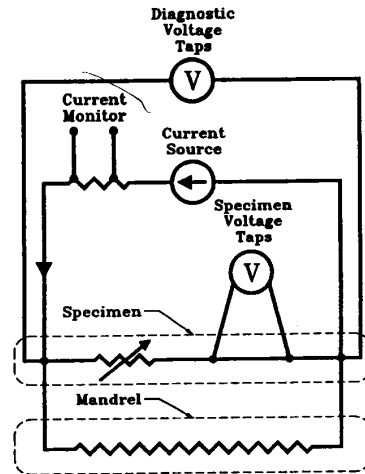

Fig. 3. Schematic diagram to explain the switching phenomenon. The variable resistance is nominally zero, but may become nonzero due to a normal state transition in part of the sample that is not instrumented. This can cause a diversion of the current flow through the mandrel, thus producing the switching behavior.

III. DETECTION AND ANALYSIS

In critical-current measurements, it is usually desirable to have a separation between the current and voltage contacts [6]. This results in active portions of the sample that are not instrumented, making this phenomenon hard to detect. However, this situation can be easily detected if a pair of voltage taps are included at the current contacts. These diagnostic taps measure the voltage across the total length of the superconducting sample (see Fig. 3). Therefore, if any portion of the sample switches to the normal state, there will be a jump in voltage on the diagnostic pair. In most cases, the voltage jump would trigger a quench detector that would reset the current to zero, thus preventing the acquisition of subsequent, erroneous data.

In our case the normal state resistance of our coiled sample ($\sim$1 m) is about 460 $\mu\Omega$. The resistance of the mandrel (thin walled tube of Ti–6Al–4V) is about 220 $\mu\Omega$ [5]. These resistances are consistent with the model described above; that is, a significant fraction of the current could be conducted through the mandrel if a portion of the superconductor is in the normal state. A voltage of 22 μV on the diagnostic pair would indicate a relatively small bypass current of 0.1 A. This gives an estimate of the upper limit of the bypass current

because we assumed negligible contact resistance between the superconductor and mandrel. A significant bypass current of 10 A would correspond to a diagnostic voltage of 2.2 mV which would result in a power dissipation of 22 mW along the mandrel. This voltage and power might not be noticed, even though the bypass current is significant.

IV. CONCLUSION

When using conductive mandrels, it is important to detect the switching phenomenon to prevent errors in critical-current determinations. A diagnostic voltage tap pair on the current contacts can be used to detect the abrupt transition indicative of transport current bypassing the sample through the mandrel. To prevent the acquisition of erroneous data, a low-voltage trip setting for the quench detector is required.

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