Quench detector circuit for superconductor testing

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A quench detector is a device that interrupts the flow of current through a superconductor in the event the superconductor reverts to the normal, resistive state. This new design has adjustable filtering and sensitivity. The input is well isolated from the output, eliminating any possible ground loop through the detector. It also has excellent noise immunity. A detector has operated with no false trips for more than two years, detecting hundreds of quenches.

INTRODUCTION

When testing superconducting wire with high current densities, it is usually necessary to interrupt sample current in the event of a quench.[1] A quench occurs when the sample leaves the superconducting state and begins a thermal runaway caused by resistive heating. Sample damage due to overheating may occur within a fraction of a second after the onset of a quench, depending on factors such as sample geometry, cooling, and thermal mass. In order to prevent such damage, an automatic device is necessary to detect the quench and reset the power supply to zero. The block diagram of a critical current measurement apparatus, shown in Fig. 1, illustrates a typical use of a quench detector in conjunction with other instruments in a critical current experiment.[2]

A good quench detector should have the following qualities: (1) Be capable of resetting the power supply rapidly enough to prevent sample damage. (2) Be able to detect both slow and rapid quenches. (3) Introduce no ground loops or extraneous signals into the system. (4) Be insensitive to noise and only reset the power supply in the event of an actual quench. (5) Be relatively simple, cheap, and easy to build.

I. CIRCUIT DESCRIPTION

Experiments have shown that all of the above qualities were incorporated in the design of the detector. The resistors are 5% tolerance, except where noted on the schematic, Fig 2. Low-noise, high slew-rate, FET-input operational amplifiers were used in the prototype, but lower quality devices would have sufficed.

The first stage of the device is a differential amplifier with a 20-kΩ input impedance and a gain of ten. The differential input tends to eliminate false tripping due to common-mode voltages. dc coupling was chosen to allow the detection of a gradual quench. The input isolation from ground is more than a gigaohm if a high-quality, high-isolation power supply or a battery power supply is used. If a medium-quality commercial power module is used, the low-voltage common or center tap should be tied to line ground to prevent common-mode voltages caused by capacitive coupling of the primary and secondary windings of the power transformer. These common-mode voltages may appear on the input terminals if the low voltage center tap is not grounded. In this configuration, the input isolation would be reduced to about 50 kΩ to ground.

The second stage of the device is a variable, third-order, low-pass, active filter.[3] This stage enables the user to choose high noise rejection, fast reset speed, or a compromise between these two extremes. Roll-off frequency selection ranging from 10 Hz to 1 kHz is adequate for typical uses.

The third stage provides a variable gain from 0.1 to 200. The gain directly determines the minimum dc trip level. Reset speed is also a function of gain. Higher gain settings increase reset speed but tend to decrease noise rejection.

An arm/stand-by switch connects the third and fourth stages. This switch enables or disables the detector without causing the power supply to reset. Some current supplies produce a large transient when initially turned on. If the detector were not disabled during this transient, it might reset such a power supply whenever an attempt was made to turn on the supply.

The fourth and final stage of the detector is an opto-coupler that isolates the internal detector circuitry from any voltage appearing on the output terminals. This section has multiple purposes: first, it virtually eliminates any possibility of a ground loop through the detector; second, it prevents any noise, emanating from the controller or elsewhere, from entering the detector via the output terminals; and third, the diodes in the opto-isolators have a threshold voltage that provides a good transition between output logic states.

The output of the quench detector is connected to the reset input of the current supply controller. The controller reset input shown in Fig. 2 is typical, but other configurations may be used as long as the input/output isolation is not degraded. This degradation may occur if any part of the internal circuitry of the detector becomes electrically coupled with the controller circuitry.

It should be noted that it is best to use a separate set of sample voltage taps for the quench detector input. These taps should not be used for data acquisition. This reduces the possibility of one system interfering with the other. Ideally, the quench detector voltage taps should be placed at the extreme ends of the sample. In this way, a quench occurring in any portion of the sample will trigger the detector.

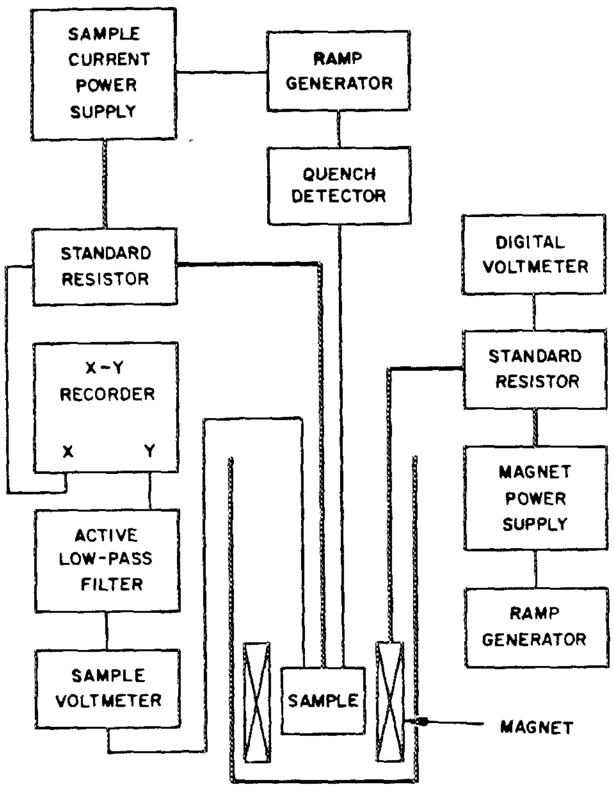

FIG. 1. Block diagram showing a typical use of a quench detector.

II. DISCUSSION

This section describes why a quench detector must be adjustable for different experimental conditions and how to go about determining the actual gain and filter settings.

Many factors must be considered in choosing the optimum quench detector gain and filter settings. The primary goal is to limit the temperature of the sample under test. The superconducting properties of the sample will be affected if the temperature is allowed to stay too high for too long. The difficulty arises in that there is no known way to calculate the minimum temperature (T_d) at which damage or change will occur. If the sample is subjected to mechanical stress, T_d can be suprisingly low, perhaps 77 K or lower. This mechanical stress can be caused by Lorentz force, differential thermal contraction, or deliberate loading. Under these conditions, sample damage is due to plastic deformation which causes a change in the superconducting properties of the sample. Since yield strength and creep rate are both strong functions of temperature, T_d is a strong function of mechanical stress.

Large nonlinearities in sample heat capacity, resistivity, normal-zone propagation velocity, heat transfer to the liquid-helium bath, etc. make rigorous mathematical analysis of the time-and-temperature-dependent sample voltage an arduous, if not impossible, task. This, in turn, makes calculation of the true optimum setting of the gain and filter imprac-

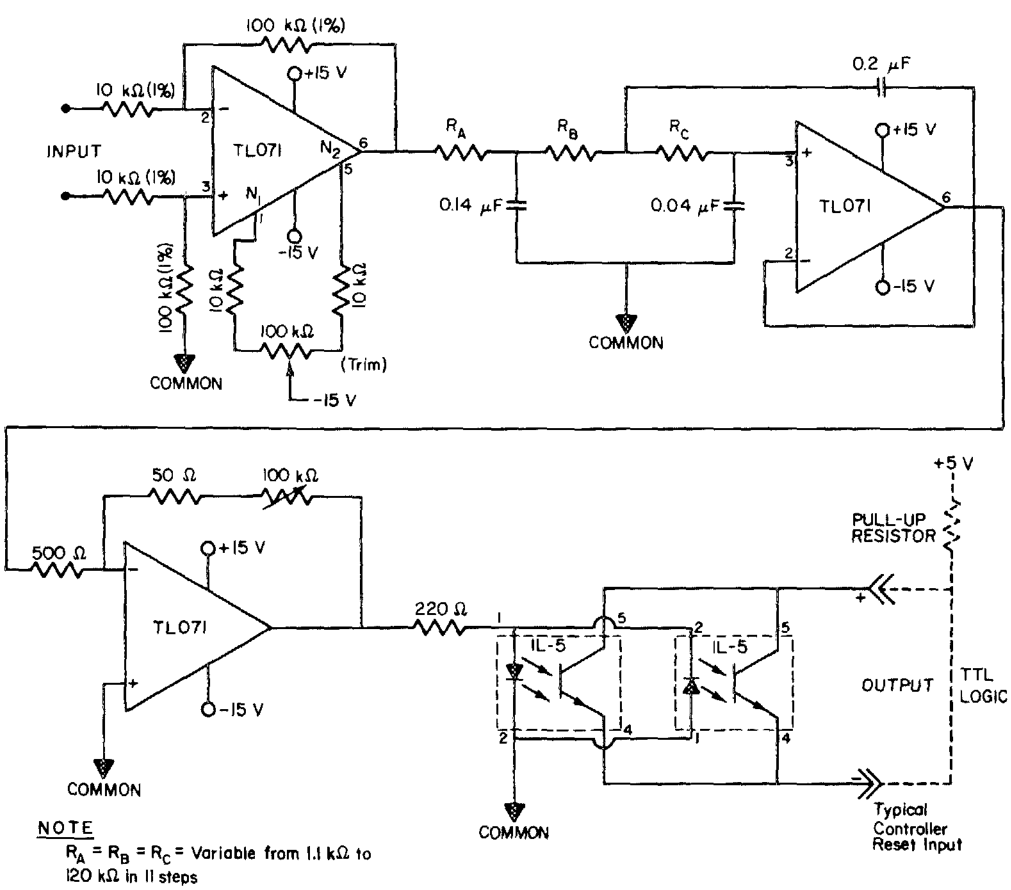

FIG. 2. Schematic diagram of the quench detector. The use of manufacturers' part numbers does not imply an endorsement by the National Bureau of Standards, nor does it imply that the devices identified are necessarily the best available for the purpose.

tical. The simplest and perhaps the most conservative approach to this problem is to estimate the low-temperature (4 K) normal-state resistance of the sample. The gain setting can be approximated as follows:

$$\text{GAIN} \cong 1.0/(RI)$$

using the estimated resistance R and test current I.

The filter setting is determined experimentally by starting at the highest (1 kHz) setting and attempting to energize the sample. The filter setting is then reduced as necessary to avoid false trip events. The distinction between true and false events can be made using an oscilloscope. If an actual quench has occurred, normal-state voltage appears along the sample before the current interruption and an inductive voltage, due to the rapid decrease in current, appears after the current interruption. If a quench has not occurred, only the voltage induced by the rapid decrease in current will be evident. If the filter setting derived by this method results in an excessively long time delay between quench event and current interruption, the filter setting selection process must be performed again at lower gain setting. The objective is to keep the sample temperature rise to a minimum, but this ideal must be balanced against the time lost due to false trip events.

The filter setting greatly affects the time delay between quench event and current shut down. With the filter section bypassed, and the sensitivity set to 5 mV, the elapsed time between the input of a 10-mV step and controller shut down is less than 30 μs. Using the same input and sensitivity settings, the delay varies from 0.38 ms at a filter setting of 1 kHz to 31 ms at a filter setting of 10 Hz. Time delay through the detector is a function of filter setting, gain setting, and input signal magnitude and shape. Time delays due to the power supply and the controller must be considered when estimating the total system time delay.

Experimental conditions determine the amount of time delay that may be tolerated. The following conditions, listed in descending order of importance, will allow an increase in the length of time that the sample may remain in the normal, resistive state without damage: (1) low sample current density; (2) low mechanical stress; (3) high sample heat capacity; (4) good thermal anchoring of the sample to a sample holder with high thermal diffusivity and heat capacity; and (5) sample and sample holder that are capable of good convective heat transfer to the surrounding liquid-helium bath.

This quench detector has prevented sample damage during many critical current and transient loss measurements. The detector appears to have all the qualities necessary for safe, reliable detection of quench and shut down of the sample power supply.

Because of the differential input, the high input impedance, and the good output isolation, no noticeable undesirable signals or ground loops were introduced into the system. Noise produced by nearby electrical equipment (drills, soldering guns, etc.), or ripple and SCR spikes produced by the sample current supply never caused false tripping when an appropriate filter setting was selected. Repeatable steady-state dc trip levels from 0.0006 to 0.500 V were possible because dc coupling was used throughout the detector.

ACKNOWLEDGMENT

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[1] *Annual Book of ASTM Standards.* Standard Test Method for dc Critical Current of Composite Superconductors (American Society for Testing and Materials, Philadelphia, 1983), B714-82, Part 2.03, pp. 595–98.
[2] L. F. Goodrich and F. R. Fickett, *Cryogenics* **22**, 225 (1982).
[3] A. B. Williams, *Active Filter Design* (Artech House, Dedham, MA, 1975).