Isolated ramping current sources for a cryogenic current comparator bridge

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The design and performance of a pair of highly isolated ramping and reversing direct-current sources for use with a cryogenic current comparator resistance bridge and dc superconducting quantum interference device (SQUID) detector are described. The current sources are floating and isolated from one another, and are internally programmed to reverse the output current while maintaining the SQUID feedback control system in lock. The sources are designed to have low zero offset in order to limit the change of the current ratio in the reversal sequence. Sources have been constructed with full-scale current ranges from 0.65 to 100 mA and have been used in the comparisons of precision standard resistors at the 0.01 ppm level.

I. INTRODUCTION

The cryogenic current comparator[1] (CCC) bridge, used with a superconducting quantum interference device (SQUID) to provide currents in a known ratio, has been accepted in national and international standards laboratories as a precise instrument for measurement of dc resistance ratios[2–7] for the past ten years. Comparisons between the quantized Hall resistance (QHR) and room-temperature standards using CCC resistance ratio bridges are being made with uncertainties approaching one part in 10^9.[8] To achieve high accuracy in establishing resistance ratios using CCC bridges, it is necessary to insure that nearly complete isolation exists between the pair of currents that flow in the comparator windings.

Earlier papers[9,10] have described double-current sources for CCC bridges that are not completely isolated from one another. For these bridges, the primary current source provides an electrical signal to control the output of the secondary source, introducing a potential measurement error when used with room-temperature resistors. Isolated current sources[5,7] have been developed for CCC bridges, but these have used the SQUID detector output to provide the entire drive signal to control the secondary source. Consequently, it is more difficult to stabilize the SQUID feedback control system in these systems.

II. CURRENT SOURCE DESIGN REQUIREMENTS

CCC bridges are now used to maintain the Ohm, the unit of electrical resistance, which since Jan. 1, 1990 has been based on the value of the QHR.[11] The measurement usually involves two ratio comparisons, the first comparing a 1-Ω Thomas-type resistor to a higher-valued standard resistor, and the second comparing that standard resistor to one of the two most stable QHR steps, with nominal resistance values of 6453.2 or 12 906.4 Ω. The high resistance value on at least one side of the bridge, and the potential error resulting from very small current leakages, make it necessary to maintain the isolation between sources above 10^{12} Ω in order to obtain an accuracy of 0.01 ppm. To achieve this isolation, each of the two sources in the system described here has an independent voltage reference circuit that controls the current output. The SQUID detector used with this design needs to provide only a small correction in order to balance the current ratio.

Throughout a CCC resistance ratio measurement, the currents in two arms of a bridge (see Fig. 1) are maintained at a constant ratio. Two currents generated by the current sources in the approximate ratio of R_S/R_P produce nearly cancelling magnetic flux when passed through the two opposing CCC windings N_P and N_S, which are of the appropriate winding ratio. The net magnetic flux sensed by the SQUID is proportional to the ampere-turns imbalance in the CCC, and when any change in the net flux is detected, current feedback is used to restore the ratio balance. However, a large change in the flux may unlock the internal SQUID control system that provides the feedback signal. For the CCC bridge system used here, an offset corresponding to 10 ppm of the full current of either source will cause the SQUID to unlock and change the lock point by an integer multiple of the flux quantum, and will invalidate that part of the measurement.

To obtain an accurate resistance ratio, the primary and secondary sources must ramp simultaneously from zero to full current and from full to zero current, for both polarities of current, while the feedback system maintains the CCC current ratio. Ramping the two main currents to the forward and reverse polarities allows differential measurement of a compensation current, which is used to balance the voltage across R_S and R_P. Differential measurements reduce the effect of linear drifts in feedback components and thermal emf offsets in the CCC bridge detector circuit. The small compensation current is produced from the isolated output of the precision nanovoltmeter (indicated by D in Fig. 1) and flows through an auxiliary CCC winding (not shown).

III. DESCRIPTION OF THE CURRENT SOURCES

Two fixed-output 100 mA sources and one variable-output current source (0.65–10.0 mA) have been constructed. Each source has a separate chassis with teflon-insulated feedthroughs and switches. Rechargeable

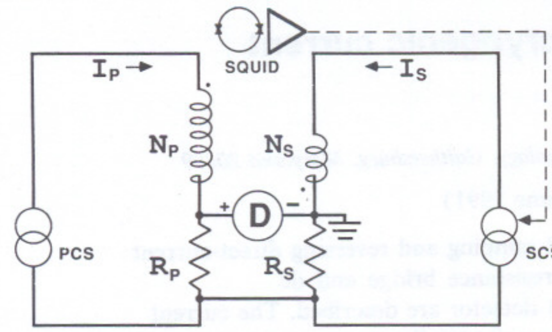

FIG. 1. Diagram of the CCC resistance ratio bridge with the primary and secondary current sources PCS and SCS. The SQUID detects the ampere-turns imbalance produced in the CCC windings. SQUID feedback to the secondary is indicated by a dashed line.

batteries, a mercury battery voltage reference, and circuitry for each source are housed inside a chassis in several shielded teflon-insulated aluminum boxes. Each source consists of an optically isolated interface, a voltage section, a current section, and a set of relays. The interfaces of two sources can receive digital signals simultaneously through a controller, which is itself optically linked to a computer (see Fig. 2). A total of three digital signals are used to initiate several possible measurement sequences. A twelve-bit digital-to-analog converter (DAC) sets a voltage to control the magnitude of the current output. The linear ramp rate of the DAC is controlled by a crystal oscillator and a number of binary counters, and internal logic signals from a sequencing delay counter control the reversal of the current using the relays.

When a current source is first turned on, the output is shunted to a resistive load (not shown) inside the source enclosure and the voltage and current are ramped up to the full level. The computer initiates a momentary pulse of the digital "ramp start" signal which causes the output of the DAC to ramp from 1.35 to 0 V. There is a 1-s delay, after which the internal logic circuit automatically starts the ramp back to 1.35 V. Following the level of the DAC voltage, the current ramps down, and it is then connected

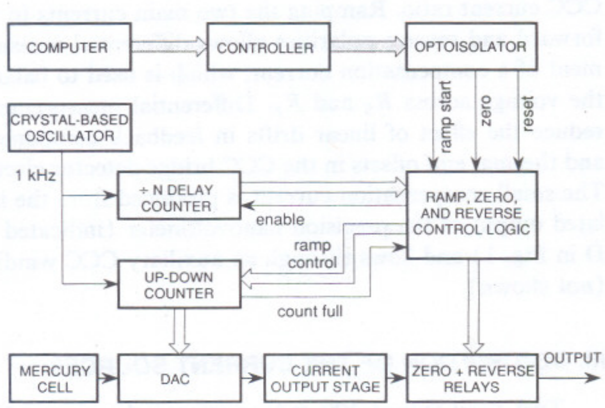

FIG. 2. Block diagram showing the control system of the current source, including the computer and controller.

to the output and ramped up for the first measurement. To reverse the current, during the 1-s delay, the current source output is first shunted to the resistive load using a mercury-wetted relay and then a second relay reverses the polarity. The current is returned to the output and allowed to settle, and the current ramps to the full level where it remains for the opposite polarity measurement.

The use of a logic circuit to control the relays allows a degree of control over the current polarity sequence. Three computer-generated digital signals control the source logic. To test systematic effects on the measurement due to the current polarity sequence and the timing of data collection periods, the computer can initiate a sequence with the "reset" signal in which the current is ramped down to zero and immediately back up with the current polarity remaining the same. Also, current to the bridge can be held at zero for an extended time, which allows disconnecting a resistor or current source from the bridge. The control signal labeled "zero" is set before the current ramps down in this control sequence and, after the DAC voltage is reduced to zero, the source output is shunted to the internal resistor and the current ramps back up to the full level.

A schematic diagram of the 0.65–10.0 mA variable-current source is shown in Fig. 3. The controlling voltage from the DAC is converted to a current and then scaled by the ratio of $R1/R2$ to produce the final current. Ten different full-scale currents can be generated by this output circuit using two current-selecting rotary switches. The low-pass filter at the input to the circuit and the low- and high-pass filters within the feedback loop are used to reduce noise and provide source stability. The 100 mA source is a similar circuit, with parallel output transistors and current-sensing resistors designed to minimize thermal drift. Identical low-pass filter components are used in the circuit of Fig. 3 and in the 100 mA sources so that all sources will have the same response to the changing input voltage of the ramp.

The source currents must be reduced to and held at zero to maintain the current ratio during the current reversal sequence. Amplifiers $A1$ and $A2$ and current sources $S1$ and $S2$ maintain small currents through scaling resistors $R1$ and $R2$ at zero DAC voltage. The field-effect transistor driven by $A2$ is selected so that sources with different output currents are able to achieve very similar performance. After assembly, the low-drift, low-noise op-amp $A2$ is adjusted, using its offset circuitry, to produce zero output current when the voltage from the DAC is zero. The zero offset of this circuit changes by less than 30 ppm, relative to full current, for a change in the power supply battery voltage from 6.35 to 6.00 V.

IV. PERFORMANCE

To measure the current source stability and noise, the output signal of a commercial dc SQUID detector is recorded without any feedback current from the SQUID to the secondary winding of the CCC. The 1 and 10 mA currents of the variable current source and the 100 mA current of one fixed source have been tested as the primary currents in opposition to the 100 mA current of the second

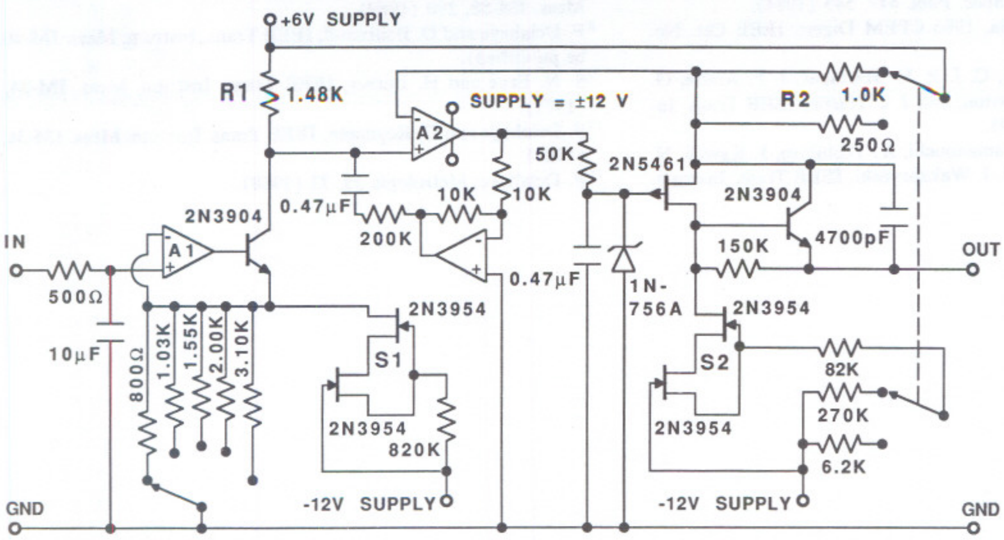

FIG. 3. Schematic diagram of the 0.65–10.0 mA current output stage.

fixed source. Single-stage RC filters with a 70 Hz low-pass cutoff are used to filter the output of each current source in all measurements. The current noise above 0.1 Hz without external feedback is sufficiently low that the SQUID internal feedback system can maintain internal lock for any of the three current ratios. With two windings of 14 turns supplied with two opposing 100 mA currents, the measured peak-to-peak (*p-p*) noise for the frequency range 0.01–0.1 Hz is about 2 ppm of full-scale current. With one winding of 1400 turns (1 mA) and one of 14 turns (100 mA), the relative noise is about 3 ppm in the same measurement. External feedback from the SQUID detector enables the bridge system to maintain current lock indefinitely at full current.

In the system used for comparisons of precision standard resistors, the SQUID feedback current is added to the output of the secondary current source at the connections to the CCC winding and resistor (see Fig. 1). The compensation current is measured and recorded under the control of the computer. Occasionally the SQUID feedback system cannot maintain lock through the current reversal

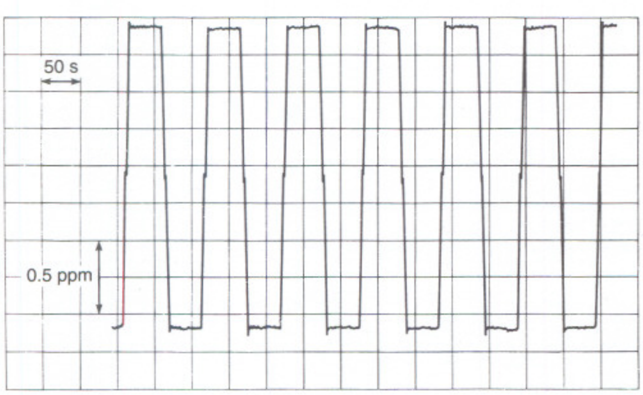

FIG. 4. The record of a precision resistance ratio measurement of 1 and 10 Ω standard resistors made using 100 and 10 mA current sources with the CCC bridge. Successive measurements are taken at positive and negative current polarity.

or in the event of external noise. When the SQUID feedback unlocks, the event can be detected by the computer because the data is punctuated by a change in the offset of the compensation current by an amount (corresponding to one or more flux quanta) that is an integer multiple of about 5 ppm in the resistance ratio.

Measurement sequences have been carried out in which the feedback is maintained continuously by the SQUID for over 100 reversals of the current. The noise level of the system is nearly the same for all three current ratios tested. Figure 4 shows a 10 min sequence of data recorded in a comparison between 1 and 10 Ω standard resistors measured at the 100 and 10 mA currents. This consists of 12 periods in which data are recorded and 12 reversals of the current polarity. The typical noise for the 45-s segments after each current reversal is 5–7 nV *p-p*, giving a one standard deviation noise level of 1 nV or 0.01 ppm.

A stable leakage current from the primary source (see Fig. 1) to earth ground averaging below 10^{-11} A has been observed and is attributed to the leakage resistance of the three optoisolators that isolate each source. This current returns to the floating primary source through the 1-Ω standard R_s and the potential short connecting the standard resistors. Placing a 1000 Ω resistor in the position of the potential short results in an error in the voltage measurement due to this leakage which produces a shift in the resistance ratio of about 0.01 ppm. The leakage current change due to the main current reversal is too small to be measured on the 1-Ω resistor alone, so leakage of the secondary source is not observed. The leakage error due to the current sources for a precision comparison between 1 and 100 Ω standard resistors is below 0.001 ppm, and could be reduced by using discrete components or fiber optics for optoisolation.

[1] I. K. Harvey, Rev. Sci. Instrum. **43**, 1626 (1972).
[2] F. Delahaye, IEEE Trans. Instrum. Meas. **IM-27**, 426 (1978).
[3] H. Seppa, 1980 CPEM Digest, IEEE Cat. No. 80CH1497-71M, 172 (1980).

[4]A. Hartland, PMFC II, NBS Spec. Publ. **617**, 543 (1984).
[5]R. F. Dziuba and J. Kinoshita, 1986 CPEM Digest, IEEE Cat. No. 86CH2267-3, 200 (1986).
[6]W. Van Der Wel, J. E. Mooij, C. J. P. M. Harmans, J. P. Andre, G. Weimann, K. Ploog, C. T. Foxton, and J. J. Harris, IEEE Trans. Instrum. Meas. **IM-38**, 54 (1989).
[7]J. Kinoshita, K. Inagaki, C. Yamanouchi, K. Yoshihiro, S. Kawaji, N. Nakashima, N. Kikuchi, and J.-I. Wakabayashi, IEEE Trans. Instrum. Meas. **IM-38**, 290 (1989).
[8]F. Delahaye and D. Bournaud, IEEE Trans. Instrum. Meas. **IM-40**, (to be published).
[9]S. N. Erne and H. Luther, IEEE Trans. Instrum. Meas. **IM-24**, 345 (1975).
[10]F. Delahaye and D. Reymann, IEEE Trans. Instrum. Meas. **IM-34**, 316 (1985).
[11]F. Delahaye, Metrologia **25**, 73 (1988).