

A Cryogenic Current Comparator Based Resistance Bridge for the Range 10 kW to 1 GW

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1. Abstract

A resistance ratio bridge based on a cryogenic current comparator (CCC) has been built to cover the range from 10 k Ω to 1 G Ω . The bridge employs a current balancing technique using an FET as a voltage controlled resistor, which has recently been modified to include a digital servo system. The performance observed so far should give a resolution of 0.1 ppm at 1 G Ω , with a total calibration uncertainty of 1 ppm.

2. Introduction

A paper in the previous BEMC conference [1] introduced a new resistance bridge in development at NPL, which extended the range of CCC measurements up to 1 G Ω . This paper presents an update on the design changes and developments of this calibration system over the last two years.

Figure 1 shows the layout of the bridge - a current ratio, equal voltage arrangement, with both arms energised by one current source. A SQUID (Superconducting QUantum Interference Device) detector senses any imbalance of the ampere-turns on the two sides of the CCC, $I_1 N_1$ and $I_2 N_2$. The output from this detector is used in a servo loop to control the gate voltage on a JFET which then operates as a voltage controlled resistor. Varying the resistance of this device allows the currents in the two halves of the bridge to be balanced to exactly match the winding ratio. A voltage detector can then record the deviation of the resistor ratio from the winding ratio. The resistors R_s match the ratio of R_x and R_y and form a combining network to ensure there is negligible potential drop along the lead linking the potential terminals of the two standards.

3. The Cryogenic Current Comparator

The main requirement of a CCC for this application is a high current sensitivity. This requires a large number of turns and careful optimisation of the geometry of the CCC [2]. The core has been wound using Cu clad and enamel insulated Nb-Ti superconducting wire of 65 μm overall diameter to permit a total of 22222 turns in a small volume. The windings are divided in the sequence 1,1,2,4,4,10,20,...,4000,10000 to allow ratio checking and yield final windings of between 1 and 10000 turns with 1:1, 10:1 and 100:1 ratios available.

The pickup coil of the CCC is matched to a commercial DC SQUID sensor (Quantum Design) and the overall sensitivity achieved for this CCC is 6.3 $\mu\text{A turns}/\Phi_0$ (where Φ_0 is the flux quantum). The ratio errors of all the windings have been measured by back to back build up from the two 1 turn windings, and in all cases were less than 10^{-9} relative error.

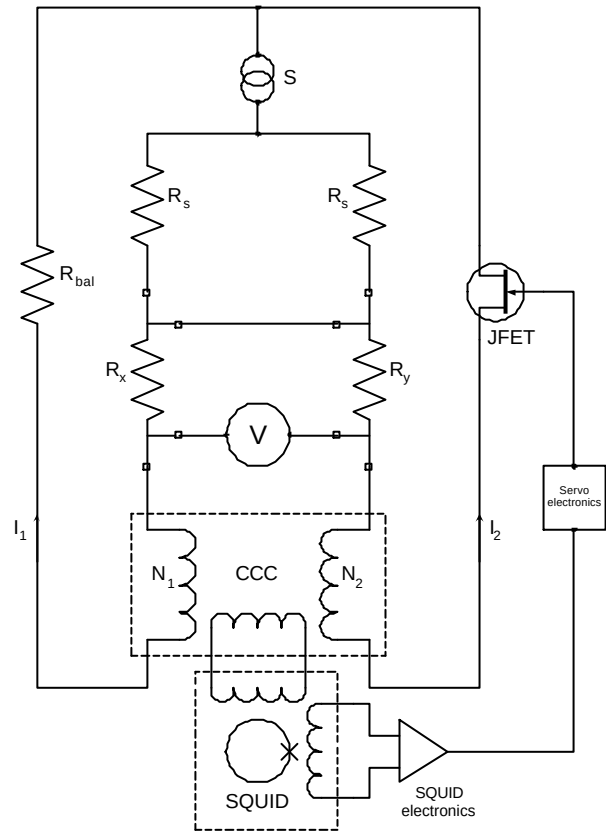


Figure 1 - Bridge Layout

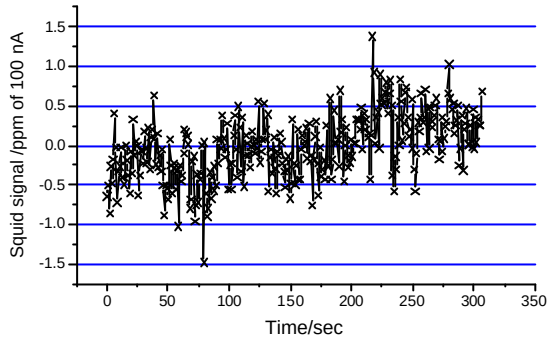


Figure 2 – SQUID noise plot

The rms noise level of the SQUID sensor is $3 \times 10^{-6} \Phi/\sqrt{\text{Hz}}$. In the ideal case, this would give a current noise for the 10000 turn winding of this CCC of $2 \text{ fA}/\sqrt{\text{Hz}}$. The noise achieved in practice is higher than this by a factor of about 10, even though the CCC is enclosed in a magnetic shield (of cryoperm material) to minimise the effects of trapped flux from external fields. The smallest signal to be measured is 100 nA and the measured noise equates to about 2ppm p-p on this measurement. This yields a resolution on a standard 5 minute measurement of about 0.1 ppm. Figure 2 shows a typical record of the squid detector noise in a 1 Hz bandwidth. The y-axis has been scaled in ppm for a measurement of 100 nA in 10000 turns.

4. Calibration of Detector Readings

The voltage detector in this bridge is a standard instrumentation amplifier feeding a 24 bit integrating ADC. The front end uses a pair of OPA111 op-amps, chosen for their very low current noise ($0.5 \text{ fA}/\sqrt{\text{Hz}}$) and high input impedance. The smallest measurement voltage used by this bridge is 3V, so detector voltage noise is not a critical parameter.

In order to avoid the need to regularly calibrate the gain of this voltage detector, each measurement is performed using two different winding ratios. One side of the bridge always uses 10000 turns, and up to 100 turns can be added to or subtracted from this in 1 turn steps. The winding ratio can thus be adjusted to match the ratio of the resistors under test to the nearest 100 ppm, and a change of exactly 100 ppm can be made to provide a calibration signal. The detector linearity and the stability of the detector gain and bridge energisation are not eliminated by this method. However, since the largest signal to be measured is about 100 ppm, if these factors can be controlled to 10 ppm, the resulting errors will be less than 1 part in 10^6 .

5. Digital Servo System

The gain of the servo using the FET resistance as its output is proportional to the bridge energisation current, and changes sign with the sign of this current. The prototype version of the bridge used an analogue servo circuit with an analogue multiplier element in the loop to correct for this gain change and sign reversal. With this system, both the bridge servo and the internal SQUID servo were able to remain locked during a reversal of the bridge energisation (over a time of a few seconds), and hence the arbitrary zero offset of the SQUID could be eliminated.

The present system takes a different approach to this problem (along similar lines to a new CCC bridge for quantum Hall measurements, also described in this digest [3]). The output from the SQUID control unit is read with an ADC, and the gate voltage for the FET is provided directly by a DAC. The servo control loop is thus implemented in software on a PC that reads the ADC and updates the DAC (the PC is isolated from the bridge electronics by NPL's low noise fibre-optic ring interface [4]).

No attempt is made to keep the servo in operation while the current is reversed. Instead, there is a separate step which determines the required DAC output values to ensure the same SQUID zero is used for both polarities of bridge energisation. Starting from zero, the bridge current is ramped up to full scale. With a sufficiently slow ramp, the internal SQUID servo does not unlock during this process, and the SQUID zero offset is maintained. The DAC value is then adjusted to bring the SQUID output back to the same offset as it had for zero current. This procedure is then repeated for the opposite sign of bridge current. Provided that this trimming can be performed such that the SQUID output does not change by more than half a Φ_0 for bridge currents of zero and $\pm$ full scale, these DAC values can then be safely used for setting the bridge balance before engaging the servo.

Once this trimming step has been performed, the measurement sequence can be started. The current can now be instantaneously switched between the two polarities, and although the internal SQUID servo will inevitably unlock at this point, the correct zero can be restored by setting the required DAC value and using the SQUID reset function, before engaging the servo and recording voltage detector readings.

6. Isolated High Voltage Supply

There is no direct connection between the bridge circuit and the instrument screen. The potential of the bridge with respect to the screen is defined by an active Wagner circuit which maintains zero potential between the screen and the junction between one of the resistors and its winding (the point on the bridge where leakage currents will cause an error). This configuration places a strict demand on the amount of interference which can be present between the screen and the 0 V line of any power supply used. Conventional mains power supplies always have a large capacitively coupled 50 Hz signal between screen and 0 V, which results in common mode currents flowing in the measurement circuit (usually resulting in unlocking of the SQUID).

This problem has been overcome at NPL (without using battery supplies) by the use of a specially designed double-screened transformer [5]. This project required higher voltages than previous measurement systems, and a new supply had to be designed using this double-screened transformer. The resulting power supply delivers ± 160 VDC with less than 100 μ V ripple (p-p) between screen and 0 V.

The supply is used to power a current source which energises the bridge. This is a modification of a previous NPL design [6], giving a bipolar output with ± 150 V compliance and a maximum current of 2 mA. The limited current output means that exposed terminals on the bridge or the standards being measured are safe to touch, even though voltages in excess of 50 V may be present.

7. Measurement Results

A full comparison of measurements made on the new bridge with those on the existing system (based on Hamon ratio devices) is presently under way. Standards up to 1 M Ω have so far been considered.

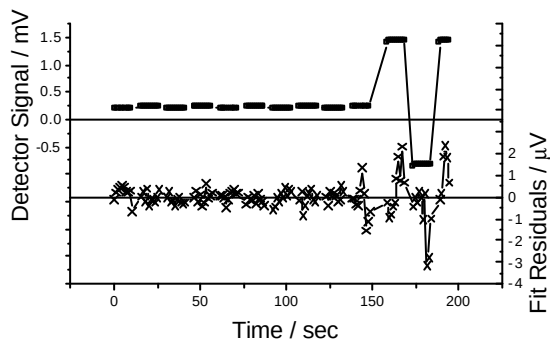


Figure 3 100 k Ω to 1 M Ω measurement

Figure 3 shows the results of a typical 10:1 ratio measurement of 100 k Ω and 1 M Ω standards. The measurement voltage is 10 V (1 mW dissipated in the 100 k Ω). The top plot is the signal recorded by the voltage detector, showing a deviation of 1.6 ppm from the winding ratio. The final reversal shows a change of 100 ppm, after the winding ratio is changed by 1 turn. The standard error on size of the fitted signal is 7×10^{-9} . The measurement was repeated 5 times, giving a mean deviation of 1.604 ppm. The standard deviation of the set of 5 measurements is 4×10^{-9} . The difference between the deviations from nominal of these two standards as

measured by the existing system is 1.4 ppm (standard uncertainty 0.7 ppm, 1 σ).

8. Conclusions

The bridge described in this paper will be used for routine calibration work for resistance standards up to 1 G Ω . A full consistency check with the existing methods (using Hamon ratio devices) will be performed. The very high accuracy of CCC ratios, combined with the ability to compare 1:1, 10:1 and 100:1 ratio measurements on a group of standards will give enhanced accuracy for resistance scaling from 10 k Ω upwards. The total calibration uncertainty for a 1 G Ω standard should be reduced from 10 ppm to 1 ppm.

9. Acknowledgement

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10. References

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