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A new technique for the automatic measurement of high value resistors

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Abstract. The development of an automatic adapted Wheatstone bridge arrangement for the measurement of high value resistance standards between 10^9 and 10^{14} Ω at voltages up to 1 kV is described. This uses stable voltage reference supplies in place of the resistors in the reference arms of the bridge. The system has been implemented at the National Physical Laboratory to replace the previous manual system without impairing the uncertainty of the measurements.

1. Introduction

The requirement is to measure decade values of resistance in the range 10^9 to 10^{14} Ω. The most stable and best characterised resistors in the NPL set are those with resistances of 10^9 and 10^{12} Ω. The 10^9 Ω standards are directly traceable to the 1 Ω national standard through a series of Hamon resistors and build-up resistor boxes. The bridge ratios of 1, 10, 100 and 1000 enable measurements from 10^9 to 10^{12} Ω to be based on the 10^9 Ω standard. Ratios of 1, 10 and 100 are used to enable measurements from 10^{12} to 10^{14} Ω to be based on the best 10^{12} Ω resistor as standard.

A conventional Wheatstone bridge has been adapted to perform DC resistance measurements under computer control, thereby minimising the amount of operator time required to make measurements in the range 10^9 to 10^{14} Ω and at voltages up to 1 kV whilst not degrading the measurement uncertainties.

The manual Wheatstone bridge previously used for this work required three resistance standards, R_1, R_2 and R_S shown in figure 1. Two low value standards R_1 and R_2, typically in the range 10^4 to 10^7 Ω form the reference arms of the bridge. When the bridge is balanced, the ratio of these is equal to the ratio of the unknown resistor to the high-value standard R_S which form the other arms of the bridge.

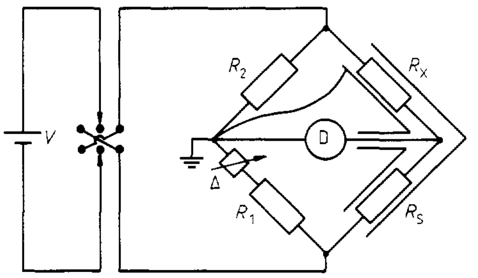

Figure 1. Wheatstone bridge circuit for measurements from 10^9 to 10^{14} Ω. R_1, R_2, low value resistors of known value; Δ, decade resistance box; R_S, standard resistor; R_X, resistor under test; D, detector electrometer. At balance $R_2/(R_1+\Delta)=R_X/R_S$.

The low-valued ratio arms and the power supply to the bridge have been replaced by variable voltage sources as shown in figure 2. The mechanism for balancing the bridge is by variation of one or both of these voltage sources, as opposed to the previous method of varying a decade resistance box Δ in the low-value ratio arms of the manual bridge.

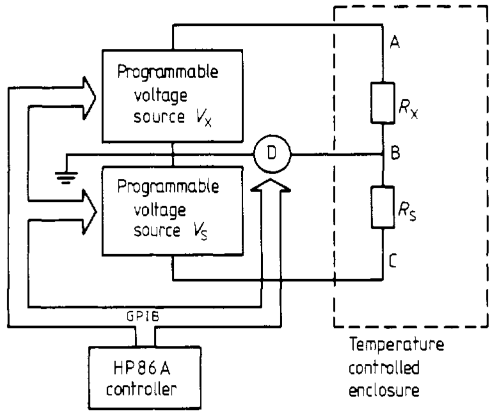

Figure 2. Automated high resistance bridge for measurements from 10^9 to 10^{14} Ω. R_S, standard resistor; R_X, resistor under test; D, detector electrometer. At balance $V_X/V_S=R_X/R_S$.

2. The bridge circuit

In the manual bridge the choice of the nominal values of the ratio defining arms R_1 and R_2 is a balance between two factors:

(i) keeping the power dissipated in the resistors low in order to minimise changes in their values due to self-heating effects;

(ii) minimising the effects of leakage resistances and capacitances in the circuit.

Leakage resistances are a possible source of error, particularly in the manual bridge. Unwanted capacitances are responsible for circuit time constants and the length of time it takes to perform a measurement. However, unless these unwanted capacitances and resistances are distributed along R_S or R_X, their effect will be lessened in the automatic bridge due to the low output impedances of the variable voltage sources.

The adapted Wheatstone bridge is shown in figure 2. The differences in the circuit from the manual bridge are that the ratio defining arms R_1 and R_2, the bridge voltage supply and the variable resistance box have been replaced by two programmable voltage sources. The sources used are Electronic Development Corporation EDC 520A IEEE 488 bus programmable devices. The linearity of these sources has been tested and changes in the outputs have been found to be within 2 PPM of changes in the set voltages.

The bridge is under the control of a Hewlett–Packard HP86A desktop computer with an IEEE 488 interface bus (GPIB) and a Hewlett–Packard general purpose input/output interface bus (GPIO). The detector is a Keithley Instruments Model 642 electrometer.

The detector is used as a current measuring instrument with ranges allowing full scale readings of 10^{-8}, 10^{-10}, 10^{-11} and 10^{-12} A, achieved by selecting from resistors of 10^8, 10^{10}, 10^{11} or 10^{12} Ω in the feedback loop of the MOSFET-based input amplifier. The insertion of current feedback by selecting one of these resistors increases the total noise from that intrinsic to the detector, owing to the Johnson noise in the feedback resistor. Therefore the value of the feedback resistor selected should be greater than the resistance equivalent of the intrinsic current noise of the detector, but if this is not known it should not be less than the effective circuit resistance (see Harkness and Henderson 1984, § 3).

The low circuit impedance of the detector means that the current flowing in each resistor is determined by the voltage source effectively connected across it. If the voltage ratio is set up such that these currents are in opposition, then the detector measures the difference between these two currents. The bridge is balanced when this current is equal to a circuit zero current reading. It is brought towards the balance point by changing the current flowing through the standard resistor, R_S by adjusting the voltage source connected across R_S. An exact balance is not sought. The out-of-balance signal is measured relative to a circuit zero. The sensitivity of the bridge is tested by making a known change to the voltage across the unknown resistor R_X, in order to change the current in R_X sufficiently to move the detector reading through the balance point. The exact balance can then be obtained by interpolation.

The accuracy of the interpolation depends on the linearity of the detector, which has been measured to be better than 0.05%. The size of the voltage change made in the sensitivity test is dependent on the nominal value of the resistor under test but the error due to the detector linearity, even in the worst case, is still insignificant.

The voltage ratio is calibrated by measuring the voltage output of the two sources, using a digital voltmeter which has previously been calibrated in terms of NPL voltage standards. With the voltage sources used, resistors can be measured at voltages up to 1 kV for bridge ratios of 10 or greater and up to 100 V for a bridge ratio of 1.

3. System description

The two interfaces used by the system have the following tasks.

(i) The IEEE 488 (GPIB) interface is used to control the voltage sources, and also to read the electrometer.

(ii) The GPIO interface has its two 'output only' ports used as follows:

(*a*) one is used to extend the programmability of the electrometer to allow computer selection of the current range required and of the electrometer input shorting switch, without adversely affecting the instrument performance;

(*b*) the second one is used to select between the low and high voltage output terminals on the 1 kV programmable voltage source.

3.1. Control software

3.1.1. Measurement parameters. Figure 3 shows a simplified flow diagram for the automatic bridge measurement procedure. The program begins by asking the operator to enter parameters relating to the measurements to be performed. The following parameters are required:

(i) the serial number for the unknown resistor (the measurement results will be stored in a file of this title);

(ii) the nominal value of the unknown resistor;

(iii) the bridge ratio being used for the measurement;

(iv) the value of the standard being used for the measurement (this is an optional parameter and if it is omitted the value of the standard is assumed to be nominal);

(v) the voltages at which measurements are required.

3.1.2. Calibration. At this stage the operator is given the opportunity to calibrate the voltage ratio. If this calibration is required, then the operator is instructed to connect the voltage supplies to different inputs of the DVM. The program stores the most recent values of corrections to the DVM readings from comparisons with the national standard of voltage, and applies these corrections to the measurements on both polarities of each voltage source.

The ratio of the two voltage sources is computed and the difference from its nominal value of 1, 10, 100 or 1000 is used as the voltage ratio calibration.

Alternatively, the operator is given the opportunity to nominate the title of a file containing the results from a previous calibration if this has taken place sufficiently recently. In this case all the voltage–range combinations requested must be present in the previous calibration.

If no calibration is requested or nominated it is assumed that the supply voltages are exact and thus that the voltage ratio is equal to its nominal value.

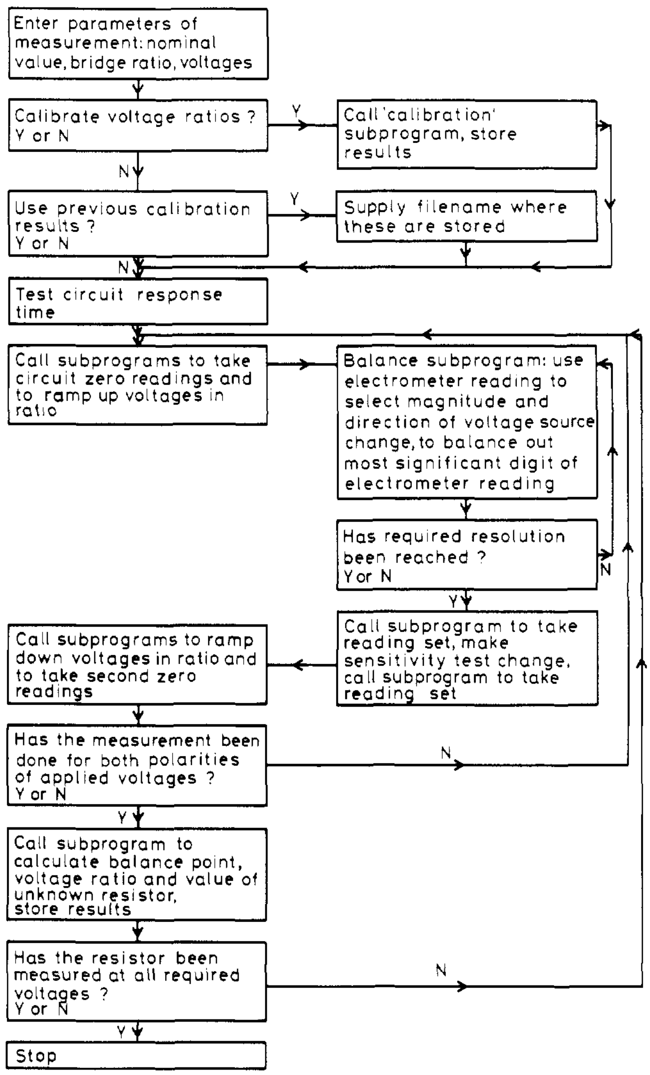

Figure 3. Flow chart of measurement procedure.

3.1.3. Circuit response. The electrometer range is now selected, by choosing the lowest feedback resistor greater in value than the equivalent resistance at the detector input of the external circuit, that is, greater than the parallel combination of R_S and R_X, as discussed in the previous section.

It is necessary to determine the response time of the circuit in order that, during the course of the measurement, sufficient settling time can be allowed before assessments of changes are made. The decay of current detected by the electrometer is monitored after the removal of a step voltage applied to the unknown resistor. This allows the time constant to be measured approximately (the time constant is less than 0.3 s for a R_S of 10^9 Ω and less than 20 s for a R_S of 10^{12} Ω) and settling times are then decided according to the sensitivity required from the measurement. Assuming an exponential decay, it is necessary to wait 14 times the time constant to be within 1 part in 10^5 of the steady value.

3.2. Measurement sequence

The measurement sequence commences with a set of readings (100 readings taken over about 30 s constitutes a set of readings) with 0 V applied to the resistors. This first set of readings is then the circuit zero reading. The voltage sources are then ramped in the required ratio to the measurement voltage. During the ramping process, the electrometer indication approaches a reading representing the departure from nominal of R_X/R_S.

Alternatively, it is possible to short circuit the electrometer input against overload whilst the voltages are switched abruptly onto the bridge, and subsequently open the electrometer input. However, it has been found that this latter method can cause a significant change in the circuit zero during the course of a measurement and is therefore not used.

The detector detects the difference between the currents flowing in the two resistors. Therefore the detector reading can be nulled by adjustment of one of these currents. The current flowing in the standard resistor R_S is changed by altering the voltage of the supply connected across this resistor. This continues until the out-of-balance reading on the detector has approximately reached the average of the first set of readings (circuit zero readings). The second set of readings is taken of this close approach to the bridge balance. Making a known change in the voltage applied to the unknown resistor, in such a direction as to pass through the balance point, measures the sensitivity of the bridge and the third set of readings is taken at this voltage.

The voltage sources are ramped down to 0 V and a set of readings (the fourth set in total) taken again of the circuit zero, thus completing the four sets of readings required. The exact balance is subsequently calculated from the mean of the two sets of zero readings which gives the point of interpolation between the averages of the second and third sets of readings. From this, a correction is made to the approximate balance readings to bring them to the balance point. A least-squares linear fit is applied to these corrected readings and to the two sets of circuit zero readings to allow the quality of the balance to be assessed.

The measurement sequence outlined is performed again with the voltage source polarities reversed. At this stage the exact balance points are calculated for both polarities of measurement, and the results stored. The program then proceeds to the next voltage at which a measurement is required.

4. Results and discussion

The bridge has been tested by the measurement of NPL resistors over the range 10^9 to 10^{14} Ω.

As was outlined in the previous section, the readings taken during the course of each measurement allow a correction to be made to the approximate balance readings to bring them to an exact balance. A linear fit is calculated on the circuit zero and the corrected balance data. The standard deviation of the fit of the data to the line is a good indication of the random component of uncertainty associated with the measurement. Possible contributions to this are noise in the measurement system and any failure of the zero readings to repeat exactly. Also any fluctuations in the temperature of the resistors during the course of the measurement will effect the standard deviation by an amount dependent on the resistors' temperature coefficient. To this extent the standard deviations are specifically for the resistors used, but these are likely to be typical examples.

From the calculated balance point the resistance ratio, R_X/R_S, is obtained. If the optional parameter, the value of the standard R_S, has been made available to the program, the value of the unknown resistance R_X can be calculated.

The results presented in table 1 were taken at a measurement voltage of 100 V and are shown separately for both polarities of applied voltage. The first pair of columns shows typical standard deviations of the linear fit to the raw measurement data. The measurements were repeated several times and the second pair of columns shows the standard deviations of ten measurements of the resistance ratio taken over a few hours.

Voltage ratio measurement results are shown in table 2. Again, the results are standard deviations of ten measurements of the ratio. These represent the random component of this part of the measurement sequence.

The results quoted for nominal values of 10^{13} and 10^{14} Ω represent a measurement against a standard of 10^{12} Ω nominal value. Therefore the results quoted must be combined with those for a determination of the 10^{12} Ω against a 10^9 Ω standard in order to maintain the traceability to the national standard. Table 3 shows combined standard deviations for measurements at each nominal value combined as a root sum of squares from tables 1 and 2, taking into account the extra build-up step required for the measurements at the highest values.

The uncertainty associated with the measured value of the unknown resistor, R_X, has a systematic component in addition to the random components mentioned earlier. Contributions to

Table 1. Standard deviations of measurement results. Polarities represent the direction of the applied voltage to the unknown resistor R_X.

Resistor nominal value R_X (Ω)	Nominal ratio R_X/R_S	Standard deviation of linear fit ($\times 10^{-6}$)		Standard deviation of ten measurements of resistance ratio ($\times 10^{-6}$)	
		+	−	+	−
10^9	1	0.6	0.6	1.1	2.4
10^{10}	10	2.3	2.3	19.1	17.4
10^{11}	100	11.6	11.3	34.6	35.7
10^{12}	1000	112	122	696	219
10^{13}	10	40	30	340	190
10^{14}	100	300	310	480	620

Table 2. Standard deviations of results of voltage ratio calibrations. Standard deviations given in parts in 10^6.

	Bridge ratio			
Voltage	1	10	100	1000
+100	0.7	1.1	1.5	7
−100	0.6	0.7	1.8	13

Table 3. Combined standard deviations of measurement results.

Resistor nominal value R_X (Ω)	Nominal ratio R_X/R_S	Combined standard deviations ($\times 10^{-6}$)		Average of two polarities ($\times 10^{-6}$)
		+	−	
10^9	1	0.9	0.8	0.9
10^{10}	10	2.5	2.4	2.5
10^{11}	100	11.7	11.4	11.6
10^{12}	1000	112	123	117
10^{13}	10	120	130	120
10^{14}	100	320	330	330

the systematic uncertainty arise from both the resistance measurement and the voltage ratio calibration sequences of the system. The resistance measurement has components arising from the linearity of the voltage supplies and also from the determination of the value of the standard resistor, R_S, relative to the national standard. At the lowest value of R_S used in this bridge (that is R_S is 10^9 Ω) this component of 6 PPM is determined by a build-up method from lower resistance values. At higher values of R_S it is also necessary to make allowance for the variation of the value of R_S with applied voltage. The voltage ratio calibration has systematic components arising from the calibration of the DVM relative to the NPL maintained voltage standard (less than 1 PPM) and also from the range stability of the DVM. The manufacturer's 90 day stability specification has been used for this component.

Table 4 shows the estimated limits of the systematic uncertainties associated with the automatic bridge. This can be combined as a root sum of squares with the 99.7% confidence limits of the standard deviation from table 3 representing the random uncertainty of the measurement, to give a total uncertainty for the measurement. Table 4 also allows some comparison of this with uncertainties previously achieved using the manual bridge. It can be seen that the results for the automatic bridge are at least as good as these uncertainties.

Direct comparison has been made between the automatic bridge and the manual bridge which it will replace. A measurement was made using a nominal bridge ratio of 1000 to assign a value to a 10^{12} Ω resistor relative to a 10^9 Ω standard and a corresponding measurement was made using the manual bridge. The results showed agreement to about 1.4 parts in 10^4 which, as can be seen from table 4, is within the total uncertainty of either measurement.

The potential problem of leakages is lessened in the automatic bridge in comparison with its predecessor. This is due to the low impedance at the output terminals of the programmable voltage supplies and to the low impedance of the electrometer being used as a detector of current. Thus leakage resistances or capacitances at points A or C in figure 2 will shunt one or other of the voltage supplies. Current is supplied without affecting the output voltage and with relatively short

Table 4. Systematic and total uncertainties for the measurements.

Resistor nominal value (Ω)	Random uncertainty ($\times 10^{-6}$)	Systematic uncertainty ($\times 10^{-6}$)	Total uncertainty ($\times 10^{-6}$)	
			Automatic	Manual
10^9	2.7	8.7	9.1	15
10^{10}	7.5	11.4	13.7	50
10^{11}	34.8	11.4	36.7	100
10^{12}	351	12	352	300
10^{13}	370	50	370	400
10^{14}	990	50	990	1000

time constants. Leakage resistance at point B in figure 2 will shunt the detector and cause a degradation in sensitivity. Point B is therefore carefully insulated and guarded as in the manual bridge. Distributed leakages along the length of the components and their cases will draw current from the voltage supplies which must flow through R_X or R_S. This effect will be the same in both the manual (see Harkness and Henderson 1984) and automatic bridges.

5. Conclusion

This paper has outlined a method of automatically measuring high value resistors in the range 10^9 to 10^{14} Ω. The operator time for performing these measurements has been reduced to a minimum whilst retaining uncertainties for the measurements which are at least as good as those for the manual Wheatstone bridge which had been used prior to this work being undertaken.

The automatic bridge has also advantages with respect to circuit time constants and leakages in the bridge due to the use of low circuit impedance programmable voltage sources and detector.

Acknowledgments

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Reference

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NPL Report DES 81