Automated NBS 1-Ω Measurement System

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Abstract—A microcomputer-controlled measurement system has been developed for calibrating stable, 1-Ω standard resistors. It consists of a direct current comparator potentiometer, a self-balancing detector circuit, and special switching networks. The measurement system is capable of comparing resistors to a precision of better than 0.01 parts per million (ppm).

I. INTRODUCTION

THE UNIT of resistance is maintained at the National Bureau of Standards by a group of five Thomas-type 1-Ω resistors. A dc current comparator potentiometer is used to compare the NBS reference group to other 1-Ω resistors under test [1]. Fifteen resistors, five of which comprise the reference group along with two control resistors and eight unknown resistors, can be connected in series with the primary circuit of the dc current comparator. The value of any resistor in the string can be determined by indirectly comparing its voltage drop to the mean voltage drop of the reference group via a stable “dummy” resistor in the secondary circuit of the comparator. The resistors in the primary circuit are measured at a current level of 0.1 A (0.01 W/resistor); therefore, a detector resolution of 1 nV is required in order to measure a resistance change of 0.01 parts per million (ppm). The Thomas-type resistors are hermetically sealed in double-walled enclosures and are very stable after being fully annealed; however, because they are constructed of manganin they exhibit significant temperature and pressure coefficients. Thus to achieve accuracies of the order of 0.01 ppm, the operator must monitor the bath temperature of the resistors along with the ambient conditions, primarily the barometric pressure. The operation of the system in the manual mode is limited to a resolution of 0.025 ppm, which corresponds to an interpolation of one-half of the last dial setting. Automation of the system has been a high priority not only because of the large work load in the calibration of 1-Ω standards and the ease with which a computer can monitor the significant test parameters, but also because of the possibility of improving the resolution and accuracy of the system.

An earlier attempt was made to automate the system by using a digital nanovoltmeter as a detector in the critical part

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of the dc current comparator circuit [2]. This detector could be readily interfaced to a computer; however, it proved unsatisfactory due to excessive ac output from the comparator which introduced noise greater than 50 nV rms in the detector circuit. The present automated system has alleviated these problems and has achieved a resolution of better than 0.01 ppm in the comparison of stable 1-Ω resistors. At this resolution, the practical measurement range of the automated system is ±500 ppm; however, it can easily be extended to wider ranges at slightly reduced accuracies. Over 95 percent of the Thomas-type resistors measured at NBS have deviations within ±50 ppm from 1 Ω. A few resistors constructed prior to 1948, whose values were based on the “international” units, have deviations at the ±500-ppm level. Thus the ±500-ppm range of the automated system satisfies the measurement needs of NBS in this area.

II. SYSTEM DESCRIPTION

A. Comparator

The heart of the measurement system is the dc current comparator as shown in Fig. 1. In the dc current comparator, a condition of magnetic balance in the core is detected by modulating the permeability of the core by a square-wave modulation current. The output of the demodulator is proportional to the magnitude and polarity of the ampere-turn imbalance and it is used to correct the slave current source to obtain a zero flux condition in the core [3]. The comparator is a commercially available unit having an adjustable 2000-turn primary, 1000-turn secondary, and a fixed 0.1-A primary current source. In the automatic mode, the primary winding is set at 2000 turns and a relay with mercury-wetted contacts is used to insert a unit winding as a 500-ppm calibration signal.

B. Resistors

The 1-Ω resistors in the primary circuit are connected in series on a mercury ring stand which is totally immersed in a specially designed circular oil bath with temperature maintained at 25,000 ± 0.003°C. A modified crossbar switch selects the appropriate potential terminals of a resistor in the primary circuit whose voltage drop is to be compared to the voltage drop of the 0.5-Ω resistor in the secondary circuit. The 0.5-Ω resistor or “dummy” is a specially designed resistor having a low load coefficient and a negligible drift during the period of a test run.

C. Detector and Feedback Circuit

The voltage difference \( V_x \) between the dummy and test resistor is detected by a photocell-galvanometer amplifier (PGA). The PGA has been modified by mounting a pair of cadmium-sulfide (CdS) photoconductive cells adjacent to the original set of photocells in order to provide an isolated output [4]. The CdS cells form two arms of a Wheatstone bridge, as shown in Fig. 2. The output of this bridge yields a sensitivity of 0.067 V/ppm. This output voltage is buffered by an operational amplifier, \( A_1 \) and then amplified by a factor of 5 by \( A_2 \). Since a 1-ppm change of resistance corresponds to a voltage change of 0.1 µV, the open-loop gain of the system \( G \) at this point is equal to 3.35 \( \times 10^6 \). It was observed that any further amplification will lead to oscillations in the feedback circuit. Amplifier \( A_3 \) provides a feedback current \( I_f \) through the 10-turn winding \( N_f \). This 10-turn winding is normally used to provide adjustable standardization settings to make the dc current comparator potentiometer direct reading. The current \( I_f \) is monitored by measuring the voltage drop across a 100-Ω resistor with a digital voltmeter (DVM). A 1-µF capacitor of PTFE dielectric connected across the 100-Ω resistor provides sufficient filtering of electrical noise in the system. The feedback system is similar to the one described in [5].

At zero flux in the core

\[
N_p I_p = N_s I_s + N_f I_f
\]

and at detector balance

\[
R_p I_p = R_s I_s.
\]

The value of resistor \( R_p \) can then be expressed as

\[
R_p = R_s \frac{N_E}{N_s} \left[ 1 - \frac{N_s}{N_p} \frac{I_f}{I_p} \right].
\]

The difference in value between resistors 1 and 2 in the primary circuit can be expressed in terms of the difference in their respective feedback currents at balance, i.e.,

\[
\Delta R_p = R_p - R_{p1} = R_s \frac{N_f}{N_s} \left( I_f - I_{f2} \right) .
\]

Since the feedback current difference can be expressed as the voltage difference \( \Delta V \) across the feedback resistor \( R_f \) then

\[
\Delta R_p = \frac{R_s}{R_f} \frac{N_f}{N_s} \frac{\Delta V}{I_p}
\]

and

\[
\frac{\Delta V}{(\Delta R_p/R_p)} = \frac{N_s}{N_f} \frac{R_f}{R_p} R_{p1p}
\]

which gives a sensitivity of 20 µV/0.01 ppm.

Amplifier \( A_3 \) is capable of supplying ±10 mA which would correspond to a measurement range of ±500 ppm using this feedback circuit. A booster amplifier could be used to increase the measurement range of the system.

It is essential to examine whether the system has sufficient
gain to provide the necessary feedback control for large resistance changes. As shown in Fig. 2, the feedback current can be expressed as

\[ I_f = \frac{GV_x}{R_3} \]  

(5)

where \( R_3 \) is the controlling element of current amplifier \( A_3 \). A change in \( R_p \) is reflected as a change in \( V_x \), i.e.,

\[ \Delta R_p = \frac{\Delta V_x}{I_p} \]  

(6)

Substituting (1) and (5) into (6) and then dividing by \( R_p \) gives

\[ \frac{\Delta R_p}{R_p} \approx - \frac{N_p}{N_f} \frac{R_3}{G R_p} \frac{\Delta I_x}{I_x} \]  

(7)

where \( \Delta I_x/I_x \) represents the normalized measurement range and \( \Delta R_p/R_p \) indicates an apparent offset caused by insufficient gain in the feedback system.

The offset for a measurement range of 150 ppm is \( 5 \times 10^{-8} \), calculated from the values given in Figs. 1 and 2. This offset can be seen as a deflection on a secondary galvanometer that is connected to the nonisolated output of the PGA. It has been observed experimentally that a 150-ppm change results in a 1-mm deflection on the secondary galvanometer. This deflection corresponds to an offset of \( 4 \times 10^{-8} \) which is in reasonably good agreement with the calculated value. For a measurement range of 2800 ppm, the offset would be 1 ppm which corresponds to a 25-mm deflection on the secondary galvanometer.

The offset problem can be eliminated if the change of current in the feedback circuit is measured for a known change in ratio. This is accomplished by measuring the change in voltage across the 100-\( \Omega \) resistor in the feedback circuit before and after inserting a unit winding in the primary circuit. For a 2000-turn primary, this corresponds to a 500-ppm change in ratio. Then the offset will not result in a measurement error if the detector output is linear and the system gain is constant. Measurements indicate that these factors contribute less than a 5-percent error for an offset of 1 ppm or less. Thus for measurements of 1-\( \Omega \) resistors over the range of 0 ± 500 ppm, the resulting error due to insufficient gain in the feedback circuit would be less than 0.01 ppm. The error would increase to 0.05 ppm for resistors that deviate from nominal by 2800 ppm.

### D. Microcomputer

The microcomputer is a disk-based system with an 8-bit microprocessor and 64K of RAM. It utilizes the S-100 bus and comprises eight parallel input/output ports, an IEEE-488 controller port, a 12-bit A/D converter port, two RS-232 ports, and a clock board. Basic I/O is accomplished with a CRT terminal and a printer via the RS-232 ports. The microcomputer is completely dedicated to running the 1-\( \Omega \) measurement system. A block diagram of how the computer interacts with the other parts of the system is shown in Fig. 3.

Interfacing of the resistor selection switch, detector sensitivity switch, ambient temperature and humidity sensors, as well as the barometric pressure transducer was done via the eight parallel I/O ports. Ambient temperature and humidity are monitored by a digital thermometer/hygrometer instrument that is interfaced to the computer through two of the I/O ports.

The barometric pressure is monitored with a transducer whose frequency output is proportional to the input pressure. Transducer temperature is determined indirectly by measuring the voltage drop across a calibrated diode that is mechanically attached to the transducer body. The pressure sensitivity of the system is 0.1 mmHg (13.3 Pa) and the corresponding accuracy is checked periodically against a calibrated aneroid barometer. The pressure transducer has been tracking the aneroid barometer to within 0.3 mmHg which is sufficient accuracy for applying pressure corrections to 1-\( \Omega \) resistors. The transducer outputs are measured by a timer/counter/DVM that is controlled by the microcomputer through a single port. The DVM, which measures the feedback current, communicates along the 488 bus. A platinum resistance thermometer (PRT) bridge monitors the oil bath temperature. The recorder output of this bridge is interfaced to the microcomputer by the 12-bit A/D converter. This approach provides a temperature measurement range of 25.000 ± 0.010°C with a resolution of 0.1 mK.

### E. Critical Switching

The critical switching area in this automated measuring system is that necessary to select and connect the potential circuits of the resistors to the PGA detector. Although the
reversal technique used for achieving a balance condition cancels the effect of constant thermoelectric voltages generated in switching this part of the circuit, it is desirable to minimize the magnitude of these voltages in order to reduce the effects of varying thermal EMF's. A proper sequence of data taking can cancel the effects of thermal EMF's that are varying linearly.

The resistor selection is of crossbar type having low thermal contacts and is similar to the one described in [6]. The activating coils of the switch are separated from the switch mechanism to reduce heat transfer to this critical area. The switch mechanism is housed in a heavy aluminum box to suppress thermal gradients.

The detector sensitivity switch consists of four latching-type low thermal relays. The relays are sealed in a heavy aluminum box filled with silicone fluid and the box is immersed in the oil bath that contains the resistors. When operating in the manual mode, all four sensitivity positions are needed to adjust the primary turns of the comparator for a balance condition. In the automatic mode, only the highest sensitivity relay is required since the feedback circuit protects the PGA detector by servoing it to a null condition. Even if the potential terminals were connected mistakenly in the wrong polarity the offset voltage at the PGA would not be enough to do permanent damage.

F. Software

The computer program is written in BASIC language using multiple subroutines to handle the data taking and data processing. The flowchart shown in Fig. 4 indicates the specific operations performed by the microcomputer.

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III. SYSTEM PERFORMANCE

The data in Table I are given to show the level of precision that is available with the automatic system. The same set of resistors were measured four times within a single day and the differences from the mean of these four series of measurements for individual resistors are listed in the table. The number of DVM readings that were taken and averaged per resistor was varied from 8 to 20 readings. The table lists the DVM readings according to the actual time sequence in which the data were taken. When a resistor was measured one-half of the total DVM readings was taken for one particular current direction, then the current direction was reversed, and after an approximate 12-s delay, the remaining half of the DVM readings was taken. The integration time per reading was 10 s. The larger imprecision for data using the 20 DVM readings is probably caused by varying thermal EMF's. No significant improvement is obtained if several reversals are performed for each resistor. The measurement range was <40 ppm.

The data in Table II indicate the differences in parts per million between the automatic and manual measurement modes. For the manual mode, an operator varies the primary turns to achieve a null balance with the PGA detector. Four measurements are taken on each resistor in the manual mode with a resolution of 0.025 ppm for each measurement. Since the automatic system is more precise, the differences are mainly due to the lower precision and operator bias in the
IV. Future Plans

Future plans include an evaluation of systematic error of the automatic system and then a re-evaluation of the uncertainty [0.08 ppm (3σ)] that is presently assigned to 1-Ω measurements at NBS [1]. The automated system has improved the precision in comparing 1-Ω resistors. With an increase in the number of measurements and the improved monitoring of test parameters that the automated system provides, it should be possible to obtain a better estimate of the possible systematic errors in the measurement process. It is planned to have the microcomputer transfer the data to a time-shared minicomputer where the data will be permanently stored and a more complex data analysis performed.

With this system it is possible to measure resistors that are located in a separate oil bath with no apparent degradation of precision or accuracy. Measurements have been made successfully on resistors in a variable-temperature oil bath with current and potential leads over 7 m long. Thus it is possible to compare resistors at any temperature against the NBS reference group maintained at 25°C. This capability is important because many international laboratories maintain their standards at 20°C and consequently it is desirable to compare standards at their working temperature. Unfortunately, the present thermometer bridge does not have the capability for computer control over a wide range of temperatures. An automatic resistance thermometer bridge [7], which can be readily interfaced to the microcomputer, is being built to measure PRT resistors over the range 0–100 Ω. Another feature of this capability is that it now becomes possible to automatically determine the temperature coefficients of resistance for standard resistors.

V. Conclusion

The automatic system has improved the precision of comparing 1-Ω standard resistors. It is expected that, after a re-evaluation of the uncertainties in the measurement process, an improvement of the accuracy level of these measurements will be demonstrated. Another advantage is that the automatic system relieves the operator from tedious repetitive measurements using a light-beam galvanometer.

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