


# A COST-EFFECTIVE AND ACCURATE ELECTRICAL IMPEDANCE MEASUREMENT CIRCUIT DESIGN FOR SENSORS

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***Abstract- A circuit design with bespoke control software is described which has delivered precision in electrical impedance measurements of ~ 10ppm, after calibration. It is low-cost and applicable to jobs such as direct measurement using a sensor whose resistance changes with some physical quantity of interest; calibration at end of line in the production of such sensors; or calibration of equipment which may be out of warranty. It was developed using resistance temperature detectors (RTDs).***

**Index terms*:* bias; calibration; accuracy; precision; drift; Kelvin 4-wire circuit; Anderson loop.**

# I. INTRODUCTION

The purpose of the circuit design described here is to provide a route to low-cost calibration of some types of measurement equipment, comparison of resistance sensor performance against expected performance and accurate measurements with well-characterised resistance sensors.

Wherever there are sensors which reflect changes in a physical quantity by changing their electrical impedance in well-characterized ways, the circuit design described here has a possible application.

Similarly, sensor performance, especially linearity, can be tested. This can be important, for instance in cases where the composition of the sensor is innovative.

Precision of ~ 10 ppm may be achieved in the measurement of the sensor's electrical impedance using an implementation of the circuit and calibration software described in this paper.

With such a high level of precision in electrical measurement, other factors limiting the accuracy of the measurement apparatus as a whole must be considered.

One such limiting factor is how well-characterized the relationship is between the quantity of interest and the sensor's resistance. If the relationship is linear, then it is easier to characterize. There are also other considerations, such as environment and drift. Temperature is an an example of a physical quantity which may be measured using a sensor whose electrical impedance changes with it in a well-understood way.

Another limiting factor is how easily and how accurately some independent measurement of the quantity of interest can be made and how closely and how reliably it can be related to a resistance value of the sensor. Additionally, the more values for the quantity of interest that can be measured independently and accurately, and the more representative they are of the range of interest, the better. There must also be an understanding of how long a time the independent measurement remains valid before it needs to be repeated.

A sensor whose variations of impedance provide useful data is easily integrated into electronic circuitry, SCADA equipment and a computer, which may then be used to calibrate the sensor through mathematical modeling of the relationship between measurements made by the sensor and 'true' values obtained in some trusted manner. In this way, a procedure for achieving high accuracy in the electrical impedance component of measurement is achieved.

Ideally, there will be a linear relationship between a sensor's resistance and the quantity it is used to measure. In this case, a small number of points of calibration of the physical quantity of interest will be needed. In temperature measurement points, such points will be changes of state of pure materials, which are actually used in the current international standards document, the International Temperature Scale of 1990 (ITS-90) [1] to define temperature points, or eutectic points of alloys, which are minimum points and have the advantage of varying slowly with changes in the ratios of the components of the alloy.

In any case, the relationship should be well understood. Otherwise, end-to-end calibration of the entire apparatus' accuracy in measuring the physical quantity of interest using a large number of measurement points will be necessary. This would be a loss of a major advantage when using resistance sensors: the ability to calibrate mostly on the basis of electrical properties.

## II. CALIBRATION OF MEASUREMENT INSTRUMENTS

The measurement circuit descibed here also has potential applications in calibration of measuring instruments and sensors. Over time, any instrument's output characteristic(s) will change and become less reliable. Therefore, measuring instruments must be calibrated periodically against a trusted instrument, that is, an instrument which has been calibrated itself [2].

Calibration of measurement instruments must be traceable, that is, they typically must be tested and certified at rationally-defined intervals against more-accurate working calibrating instruments, which are in a chain leading back to primary standard instruments, which conform to international standards in how they make measurements. Comprehensive calibration records are essential [3], although it is perhaps permissible to say that in most cases they are not maintained, leading to inaccurate measurements or the unnecessary expense of buying new equipment.

In general, an instrument calibrated by another instrument is considered at least 4 times less precise. This is reflected in the *4:1 rule* [4].

Being traceably calibrated allows equipment to make measurements which can be compared with measurements made around the world.

On the other hand, there is an obvious advantage to calibration methods which get around the need to refer back to a primary test centre. One example is the changes of state of certain pure

materials which define a series of temperature points and provide, at least in principle, a route to decentralized calibration of temperature measurement devices.

A multimeter is a versatile instrument and once calibrated it serves to ensure accuracy in the measurement of sensor resistance by the circuit described here. This contributes to the achevement of accuracy in measuring temperature (or some other physical quantity).

For the electrical measurement calibrations carried out on the circuit described here, the calibrating device was the Agilent 34461A 6½-digit multimeter [5], with a documented nominal impedance-measurement inaccuracy, based on calibration performed less than 2 years beforehand, of ±0.01% (100 ppm) of the measurement ±0.004% (40 ppm) of the range.

## III. ELECTRICAL IMPEDANCE MEASUREMENT

Electrical impedance measurement can be achieved by measuring two quantities - a current driven through an impedance and the resulting voltage across that impedance – and dividing one into the other. However, measuring current directly is not always easy to do accurately. Instead, a voltage across a precisely known resistance is measured, and the following equation is used to determine *R*:

$$R = \frac{V}{V_{ref}} R_{ref} \tag{1}$$

See Figure 2.

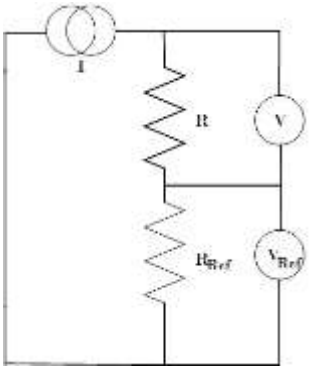



Figure 2. Circuit to measure resistance

This circuit is also ratiometric, since the result is obtained by dividing one voltage measurement by another. The 3rd factor in the equation, $R_{ref}$, is a resistance, which in practice can have a drift

factor of less than 1 part per million (ppm) per degree Centigrade. Over a limited temperature range, the figure is as low 0.05ppm/° C.

The most precise, repeatable methods of measuring electrical potential difference (voltage) and electrical impedance which have been achieved are used to define units of those quantities in the International System of Units (SI) [6], [7].

In many cases in the real world, the impedance to be measured is not always located conveniently for measuring. Long connecting wires are often required to connect it to the measuring circuit or device. A case in point is temperature measurement. The Kelvin 4-wire circuit allows the use of long leads while minimizing the loss of accuracy [6]. See Figure 3, in which the effects of the lead resistors are minimized, both because they do not affect the constant current being driven through the target impedance, and they are in series with the very high (10MΩ) internal resistance of a voltmeter. Equation 1 above again applies.

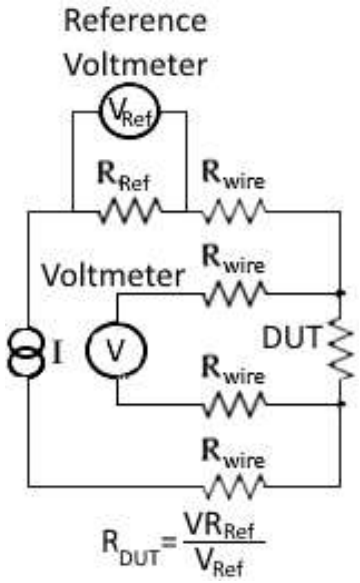



Figure 3. 4-wire circuit with ratiometric measurement

Perhaps the best-known type of highly accurate impedance measurement circuit is the Wheatstone bridge.

The Anderson Loop is an alternative to the Wheatstone bridge. It is based on the Kelvin 4-wire circuit concept [8]. See Figure 4.

It uses a double-differential linear electronic amplifier to obtain a difference between two voltages. Its accuracy is limited by the gain accuracy and CMRR of the amplifier. In instrumentation amplifiers, CMRR performance can be poor at higher frequencies [9].

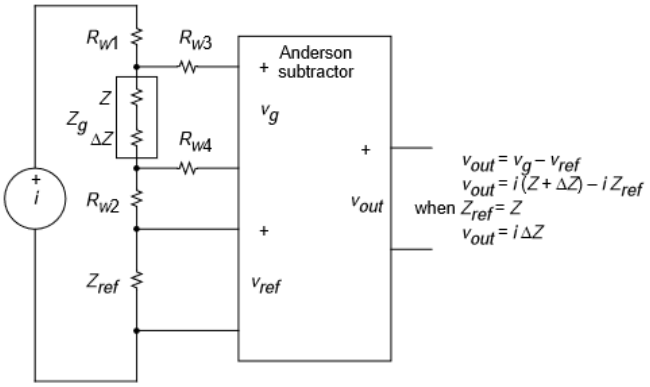



Figure 4. Anderson loop measurement circuit topology

The circuit design presented in this paper (see Figure 6) incorporates elements of ratiometric measurement and the Kelvin 4-wire circuit decribed above. It is based on a design which was applied by its originator to temperature measurement [10], and was itself based on the concept of the Anderson Loop.

It also includes a bias-elimination function in that the output voltage is proportional to the difference between the sensor resistance and some non-zero reference value.

## IV. CIRCUIT DESIGN AND IMPLEMENTATION

The circuit design presented incorporates the facility to simultaneously reverse the excitation current and connections to the inputs of the instrumentation amplifier component, to compensate for voltages created by the thermoelectric effect, an important consideration when connections are made over long wires between a circuit at room temperature and a sensor at much higher temperatures, in an oven, for example. The Kelvin 4-wire circuit's minimizing of the effect of connecting-wire resistances also applies to the resistances of the switches inserted to implement the current and measurement reversals.

In some diagrams herein, the connection of the circuit through switches to the sensor, or device under test (DUT), is represented with a schematic shorthand, as shown in Figure 5. The four wires connecting to the DUT may be quite long, with the DUT (the sensor) located where it is needed.

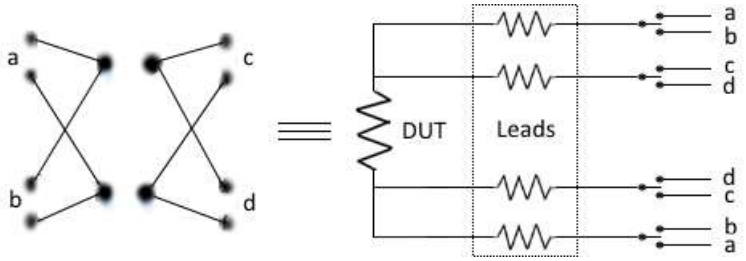



Figure 5. Schematic shorthand representation of Kelvin 4-wire connection to DUT

It further incorporates switching elements (n-channel enhancement mode MOSFETs). These enable controlling software to adjust the circuit so that it can measure narrow ranges around certain points of interest, and the additional facility of pulsing, for combating the self-heating effect.

The instrumentation amplifier in the circuit both amplifies the difference between the voltages applied to its inputs and refers its output voltage to ground. The formula for the resistance of the sensor is then:

$$R = \frac{R_{ref}}{G}\left(\frac{V_{out}}{V_{ref}} + 1\right) \tag{4}$$

where $R_{ref}$ is the reference resistance; $G$ is the gain of the amplifier; $V_{out}$ is the difference, as measured by one of the ADCs, between that voltage and the voltage across the reference resistance and Vref is the voltage across the reference resistance as measured by the other ADC.

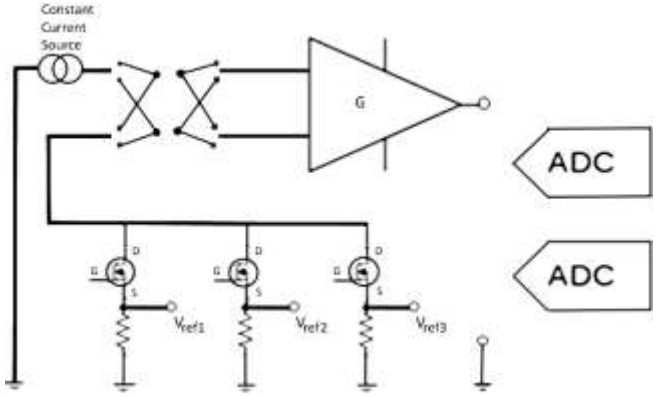



Figure 6. Programmable Anderson Loop Variant Circuit

Bias has been eliminated from the measurement of $V_{out}$. This allows adjustment of the range of the ADC, and therefore also of its nominal resolution in voltage terms.

The DAQ hardware used in our experiments may serve as an example of the improvement in resolution which the removal of bias can bring in practice. The input voltage range can be set to the following values (with the rated absolute accuracy figures included in brackets) [11]: ±10V (500μV), ±5V (300μV), ±2.5V (200μV), ±1.25V (100μV), ±0.625V (60μV), ±0.3125V (50μV), ±0.15625V (40μV) and ±0.078125V (40μV).

Sofware control of the MOSFETs and switches is achieved through the use of standard digital outputs, where 5V or 0V is asserted, depending on logic in the controlling computer program.

The location of the n-channel enhancement mode MOSFETs in the circuit has the advantage that their on-resistances may be ignored, provided they are not very high, since the current across them is not measured. However, this comes at a cost because the voltage at the source of each MOSFET varies with the current passing through the reference resistor and it must be guaranteed that the MOSFET will be open and current will flow. See Figure 7 [12].

It can be seen that if $V_{GS}$ is very low, current is cut off altogether, but also that for somewhat higher values, saturation still occurs at low values of $V_{DS}$ and the current through the circuit may be choked off.

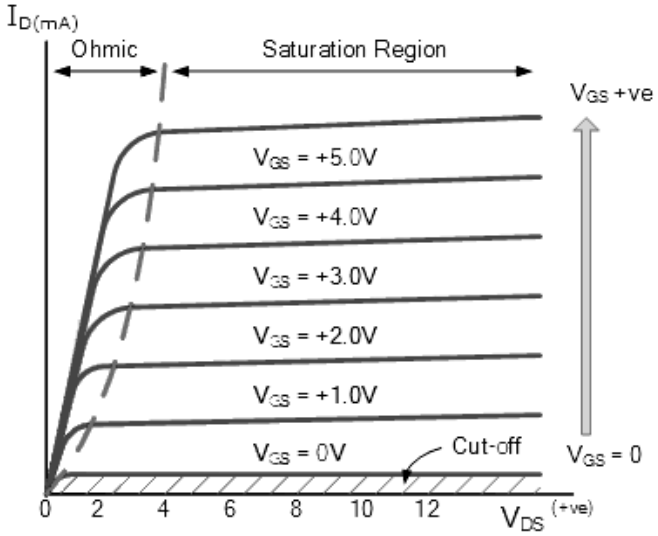



Figure 7. Enhancement mode NMOSFET drain characteristics

To get around this, a higher high voltage can be applied to the gates of the MOSFETs. In experiments, the Measurement Computing USB-2408 DAQ was used, in which an external voltage connected via a pull-up resistor may be switched through by the digital input/output ports. See Figure 8.

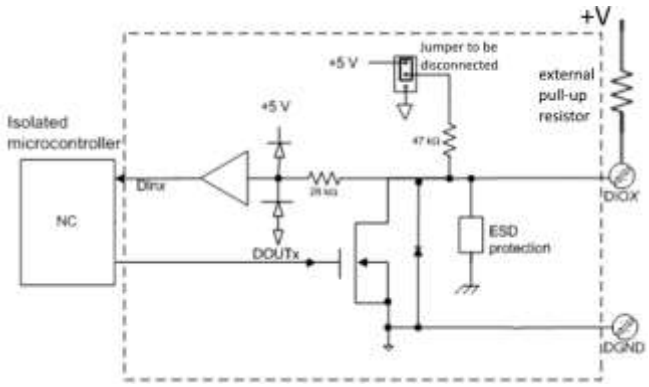



Figure 8. An external voltage through a USB-2408 DIO

The MOSFETs used in the prototype have extremely low on-resistance (0.49mΩ [13, p. 3]), meaning they add negligibly to the effective reference resistances in a series connection, which were of the order of 1kΩ. They will also very probably contribute negligibly to drift, although this has not been verified. Because of this, another configuration, with the MOSFETs connected between the reference resistors and ground is possible. It has the advantages of not needing a separate ADC – or rewiring for every change of reference resistance – for each resistor (this also prevents combinations of resistors to achieve desired resistances) or special care with regard to the voltage applied at the gates. See Figure 9.

The ADCs were configured as differential for detecting the difference between the voltage at the output of the instrumentation amplifier and the voltage at $V_{ref}$, and single-ended for detecting the difference between the voltage at $V_{ref}$ and ground. Although this configuration worked in the experiments we conducted, it seems to be in breach of recommended practice, according to the ADC equipment manual, of connecting the low pin of a differential ADC to ground via a 100kΩ resistor [11]. A fully differential ADC should ideally be used. See [13], for example, for a discussion of fully differential ADC inputs (among other types).

The current source was implemented with low-cost components: the Texas Instruments LM234, a diode and two resistors [14]. High precision, interestingly, was still achieved.

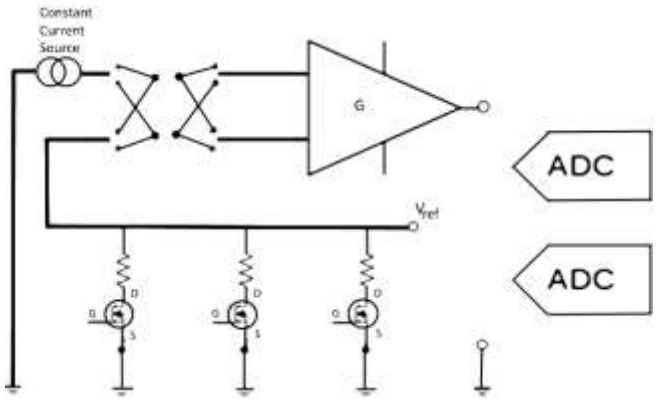



Figure 9. Programmable Anderson Loop variant circuit

## IV. HANDLING SOURCES OF ERROR

Measurement in general is prone to a number of sources of error. The term *error* also has two somewhat different meanings: systematic error (or statistical bias) is error that occurs every time until it is eliminated, and undermines accuracy even if the measurements are very precise; random error is the inverse of precision.

Examples of sources of random error include measurement digitization, component tolerances, thermal noise and current noise. Examples of sources of systematic error in electrical measurement include the power supply, transients, resistor self-heating, load life stability, reactance and voltage coefficient.

An example of a source of both random error and systematic error is non-linear relationships between something actually measured such as voltage and what it represents, such as temperature. Ideally, the relationship will be linear or very nearly linear and well-characterized. As discussed above, this is an important consideration for the circuit described in this paper.

Platinum RTDs are an example of sensors with a very well-understood, near-linear relationship between temperature and resistance. A quadratic simplification of the Callendar van Dusen equation is universally accepted as accurately describing it for temperatures above 0°C [16]:

$$R_T = R_0(1 + aT + bT^2) \quad (5)$$

where T is the temperature in °C, RT is the resistance at T, a=3.81×10$^{-3}$ Ω/K, and b=-6.02×10$^{-7}$ Ω/K$^2$.

Besides measurement error and random variability, there is another source of error: modelling error, which is the uncertainty that the mathematical model predicts reality [16]. Also, there is human (or "gross" or "personal" [17]) error.

Efforts to minimize errors focused on (1) calibrating the measurement system as a "black box" (2) taking steps to minimize specific sources of error wherever they could be identified and (3) identifying areas where accuracy depends on a correct characterization of the bahaviour of a component of the measurement system.

It has been assumed in the development and testing of the circuit, that the relationship between the quantity of interest and the impedance of the sensor will be well understood. (Ideally, it will be linear). In cases where that is true, it follows that precise calibration of the circuit's measurements of electrical impedance over the whole of range of expected impedances, combined with accurate calibration of the circuit's measurements of a small number of well-chosen values of the quantity of interest, will result in accurate measurements of the quantity of interest over the intended range.

Making independent measurements of the quantity of interest, which are known to be accurate, and matching them to measurements made by the measuring system calibrates it as a black box. For example, detecting changes of state of pure materials provides a means of accurately determining certain temperature points [19].

The electrical impedance measurement part of the circuit can also be calibrated as a black box, by replacing the sensor with known resistances, whose values can be further verified by measurement with an officially calibrated measurement device. The measurements and their differences from the calibrated values can be analysed snd corrected for, using postulates such as that the errors follow some linear or quadratic formula.

Measurement digitization was effectively eliminated by the use of a 24-bit ADC, giving a nominal digitization error of 1 part in over 16 million. The rated precision of the ADC is lower (see discussion above).

The effect of some component tolerances was reduced by the ratiometric nature of the measurements. However, it was clear in theory and verified in practice, that a highly stable reference impedance is essential.

The effects of transients and noise were combatted through averaging and the robust statistical technique of discarding a percentage of outliers.

The effect of resistor self-heating was combatted by pulsing the excitation current.

The thermoelectric effect can cause voltages to appear on conductors with temperatures gradients along them, and introduce errors in electrical measurements. This is a problem in cases where an RTD is being used to measure high temperatures while connected to a measurement circuit at room temperature. It was combatted by allowing the excitation current and measurement polarity to be reversed together.

The possibility of human error was reduced by means of the automated nature of the recording and timestamping of measurements, and the direct control of the calibrating Agilent 34461A multimeter by bespoke software, over USB.

Rather than modeling the circuit's error sources, the unit was calibrated as a black box from the terminals of the sensor or test resistors to the computer recording and timestamping the readings. After obtaining a suite of measurements, linear regression analysis and quadratic curve fitting were performed.

The user interface was constructed so that the user could first calibrate the circuit, then, later, test it and finally use it to measure some unknown impedance. The calculations were made in Excel in the calibration stage and in LabVIEW in the test phase to guard against artefacts in the code. Quadratic curve fitting was found to yield results in the test phase consistently better than 20 ppm, so that when performing a measurement, there can be confidence in the result. See Figure 10 for a graph of some calibration results.

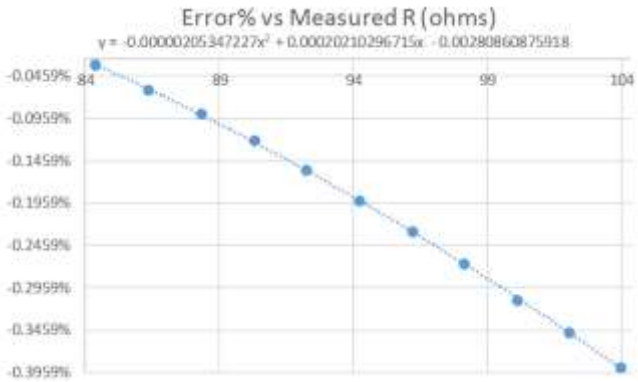



Figure 10. Quadratic curve-fitting graph

## V. BLACK BOX MODE

Of course, the electrical impedance is not the quantity of interest being measured and therefore, whether it is accurately measured by the circuit or not is not important *per se*. If the relationship between the sensor's impedance and the quantity it is measuring is well-understood, and especially if it is linear, the only calibration necessary is of the quantity of interest. If the relationship is not well understood, calibration of the whole system, comprising sensor, circuit, ADC, computer and software could be treated as a black box and calibrated, but it is not expected that the results would be very accurate, unless the sensor's resistance varied strictly linearly with the quantity of interest. That said, this has not been tested here.

## V. DOUBLE BIAS ELIMINATION

A high level of precision of electrical impedance measurement has been achieved by the circuit design described above. It was achieved, in part, by the elimination of bias when measuring the output voltage. Ideally, however, the bias in the measurement of the voltage across the reference resistor should also be eliminated, since it is nominally constant. The equation for the sensor impedance will then be

$$R = \frac{R_{ref}}{G}\left(\frac{V_{out}}{V_{ref}+\Delta V_{ref}} + 1\right) \quad (6)$$

where $V_{out}$ and $\Delta V_{ref}$ are the measured quantities.

A variant was tested, in which a second current source and reference resistor were included. It was hoped that this design might even reduce the need for very precise reference resistors since two similar resistors could be expected to drift with temperature by the same amount, but no improvement in the precision level was detected. See Figure 11.

An alternative way to achieve double bias elimination is to use stable voltage source(s), to provide $V_{ref} = IR_{ref}$ as in Figure 12. The drift of the output of such devices can be very low. See [20] for an example, where the output is stable to within 1ppm/° C.

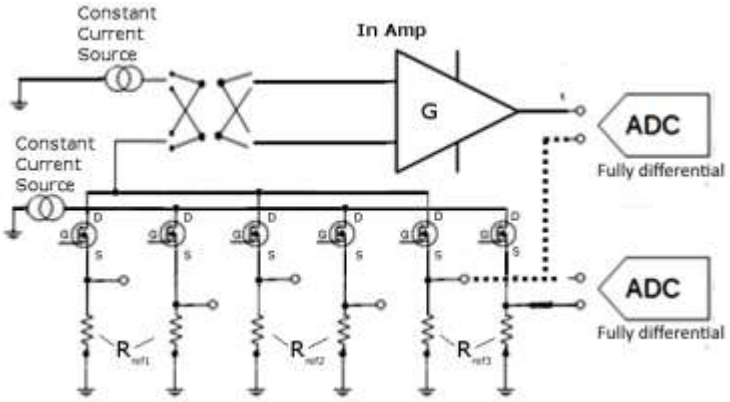



Figure 11. Double bias elimination with matched current sources

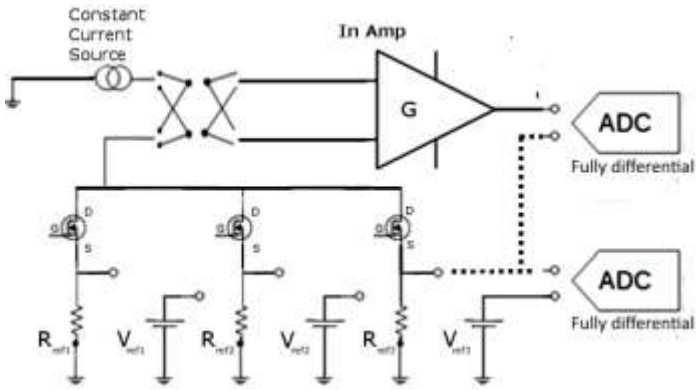



Figure 12. Double bias elimination with reference voltage

## VI. CALIBRATION OF SENSORS – A CASE STUDY

Sensor technology is continually advancing. As a result, new types of sensors are appearing which are cheaper, or more accurate, or apply to wider measurement ranges than before or have novel applications. In all these cases, the wide experience built up over time of a particular sensor type is no longer necessarily valid, and more comprehensive calibration tests become necessary.

For example, the investigations leading to this paper were originally prompted by a challenge presented by the development of a new type of RTD. This new product sought to extend the classic Callendar van Dusen near-linear temperature response of platinum RTDs, which is widely accepted, to temperatures not normally tested by platinum-based sensors.

It became apparent during development that the behaviour of the new kind of RTD could not be trusted to be the same as a platinum-based sensor, either in terms of the actual values of

resistance presented at various temperatures or (especially) in terms of the response being linear or near-linear. Because of this, some new method of calibration was needed.

Platinum-based RTDs are widely used and the relationship of their resistance to temperature is particularly well-understood. This lightens the requirement in terms of end-of-line testing and allows it to be more limited than it might be otherwise.

Melting ice (0° C) and boiling water (100° C) are used to define their temperature points in ITS-90 [19]. Tests against these reference points were considered adequate, even though the sensor might be expected to measure much higher temperatures in some real-world application, because the behaviour of platinum RTDs is so well understood.

From the above, it can be seen that the development of a new variation of an established type of sensor not only introduced the challenge of testing whether it could successfully extend the measurement range, but also meant the new variant had to be proven to work across the original measurement range. In fact, the relationship between the sensor's resistance and temperature needed to be characterized and ideally a new formula, similar in form to the Callendar van Dusen equation, would be contructed.

The convenient reference points of melting ice and boiling water needed to be supplemented. The solution found was to use other temperature points defined in ITS-90 by changes of state of materials, besides melting ice and boiling water, in order to fulfil the calibration function at higher temperatures.

This application serves as an example of the method that needs to be adopted generally, in order to calibrate sensors using the circuit described here, with a resistance sensor and a computer system for automated test: (1) acquisition of knowledge of the relationship between the sensor's resistance and the physical quantity it measures, (2) precise, preferably accurate measurements of the resistance of the sensor at a range of values of the quantity and (3) accurate measurements of those values made in some other, independent way.

## VII. CONCLUSIONS

A circuit has been described in this paper which delivers precise measurement of a resistance at low cost. It incorporates a number of facilities to ensure precision and accuracy, such as bias

removal, ratiometric measurement, a Kelvin 4-wire connection, a.c. measurement and pulsing of the excitation current. The building and testing of a prototype has been described and representative results have been presented showing a very high level of accuracy after calibration with a 6½-digit multimeter.

A method of calibration of RTDs and experiments to verify that it is viable have been described. Finally, a refinement has been proposed which may yield even better precision by means of a total elimination of measurement bias.

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