

COMPOSITE MILLIOHM-METER FOR RESISTANCE MEASUREMENT OF PRECISION CURRENT SHUNTS IN INDUSTRIAL ENVIRONMENT *

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Abstract. *A composite milliohm-meter (Com-mOhm), based on standard four-wire Kelvin resistance measurement method, was developed for measurements of precision current shunts used in an industrial environment. The system is comprised of a precision, temperature compensated, low drift, high stability 100 mA current source and a 4 ½ digit commercial multimeter. Due to the set of specific demands and conditions concerning the industrial applications of precision current shunts, standard measurement equipment and methods could not be implemented. The composite resistor standard was used for temperature stabilization of the precision current source based on precision voltage reference REF102. The measurement precision of ± 0.1 milliohms is observed during measurement of 20 milliohm current shunts.*

Key words: *calibration, milliohm-meter, precision current source, four-wire resistance measurement, current shunt, measurement uncertainty*

1. INTRODUCTION

This paper is an extension of the conference paper [1] and the lecture [2]. It is based on the experience in solving the specific task described, which required a unique solution within the projected budget and adapting to working conditions in industrial environment.

Laboratory for Metrology and Chair for Electrical Measurements at the Faculty of Technical Sciences in Novi Sad have continuing cooperation with companies in the field of instrumentation, metrology and control of industrial processes. User demands often require finding non-standard solutions and constant innovation in the field of electrical measurement, as described in [3] and [4].

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2. PROBLEM DESCRIPTION

For the development of precision CNC machine motors and other devices where measurement of direct current (dc) with high accuracy is required, an automated 16-channel control system has been developed within a company in the field of automation of industrial processes.

An industrial system for precision motor control is shown in Fig. 1.

Each system control channel is consisted of:

1. Microprocessor control module (UM), common to all 16 channels.
2. High-resolution current driver (PS), digitally controlled by a microprocessor system which is part of the UM.
3. Precision CNC motor (M) being controlled by current I_M .
4. Serial shunt resistor (R_S) with 20 m Ω resistance and tolerance of $\pm 0.5\%$.
5. Module for monitoring (MM) of voltage drop U_m on shunt with the feedback to UM.
6. External process control unit (E) - control desk.

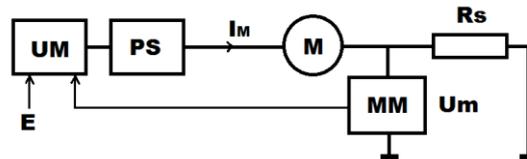


Fig. 1 Block diagram of an industrial system for precision motor control

Control module UM receives command from control panel E and adjusts the corresponding digital signal that sets the required dc current I_M of power driver PS. This current drives the motor M and creates a voltage drop U_m on a precision current shunt R_S , which is measured at one of the 16 analog inputs of the monitoring module MM. Using A/D conversion, this voltage is converted into digital signal and is forwarded to UM, creating voltage feedback line. This signal is compared with the value set by the user and, the output of the PS is adjusted to the required value, if necessary. The projected accuracy of the system is $\pm 0.1\%$ of the current I_M .

3. PROBLEM ANALYSIS AND STANDARD SOLUTIONS

The company noted a measurement related problem when producing precision low resistance current shunts. This resistance has to be measured with accuracy better than $\pm 0.5\%$. A task is defined to create an instrument that will successfully measure the resistance of a shunt during its production.

The voltage measurement range of the monitoring module is 200 mV, so for an operating current of up to 10 A, it is necessary to produce a shunt resistor of (20 ± 0.1) m Ω . Resistance measurement with resolution of 100 $\mu\Omega$ is an extremely complex requirement, even for the most modern instruments, [5] and [6].

A high performance laboratory multimeter standard, such as Fluke 8846A with 6 ½ digits resolution, at the lowest ohms range of 10.00000 Ω , has a sensitivity of 10 $\mu\Omega$ [7].

The price of this instrument is over \$2000. Procurement of this (or similar) instrument was not an option for the company, due to the budget for the realization of this instrument was about 10 times lower.

Another significant problem was imposed upon the analysis of the production process of mounting shunts (a shunt with associated mounting bracket, which also has its finite contact resistance). The mounting shunt consists of a piece of copper alloy (shunt), which is mounted in the brackets. The shunt is fixed with screws passing through the top of the bracket and pressing the copper against the contacts at the bottom of the carrier, as in Fig. 2. Each contact has a soldering point attached to it, enabling connection to the rest of the circuit. The mounting shunt is shortly called *shunt*.

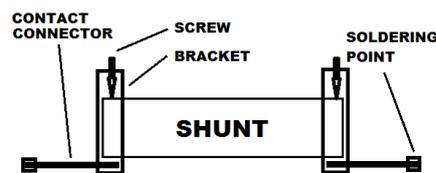


Fig. 2 Mounting shunt components

Pieces of copper alloy are procured prefabricated to the resistance of $(15 \pm 5) \text{ m}\Omega$. It is possible to obtain prefabricated pieces of alloy of higher accuracy, but the price is exponentially higher. The company decided to purchase cheaper products, expecting "easy, quick and cheap" process of adjustment to the desired tolerance. In order to achieve the desired accuracy of the shunt, the copper piece is mounted in the bracket and its resistance is manually increased by cutting into the body of the alloy and by filing the surface of the shunt with a fine diamond-coated file. During this final treatment, the shunt resistance is continuously measured, i.e. dc current is continuously passed through it.

This is the reason why two basic methods of measuring resistance are not possible in this case:

The first method, using an industrial milliohm-meter [8], implies that during handling of the shunt and its processing, constant high current (up to 2 A) is passed through it, which can endanger the safety of workers and surrounding workplace, consumes a lot of energy and leads to a large thermal dissipation.

Another method is the Wheatstone bridge, [9] and [10], one of the most commonly used bridge methods. Even today, high precision measurement bridges are produced to cover wide range of resistances (from $\mu\Omega$ to $\text{G}\Omega$), for industrial and laboratory applications, e.g. [11] and [12]. With three resistors of a known resistance, the value of the fourth (unknown) resistance can be determined very precisely, as in Fig. 3. The values of the resistors R_1 and R_3 are known and fixed, while the resistance R_X is measured. The bridge is in balance when there is no current flowing through the galvanometer G in the diagonal of the bridge. The condition of the bridge balance is given simply as the product of R_1 and R_X must be equal to the product of R_2 and R_3 . This is achieved by using a variable resistor R_2 for bridge balancing. If the resistors R_1 and R_3 have the same resistance value, the bridge is in the balance when $I_G = 0$, and resistance R_2 corresponds to the value of the unknown resistance R_X . The value of unknown resistance can be determined as:

$$R_x = R_s \cdot R_2 / R_1 \quad (1)$$

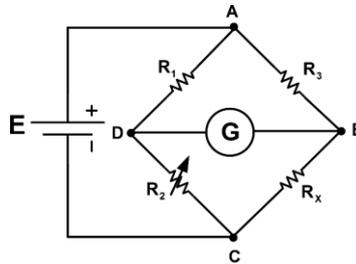


Fig. 3 The Wheatstone bridge

In this case, the measurement would seem to be possible by simply selecting equal values of the resistors R_1 and R_3 , with the value of R_2 adjusted to $(20 \pm 0.1) \text{ m}\Omega$. It turns out that it is not possible to perform such delicate measurements due to mechanical vibrations during the manual processing, as there are sudden changes in the contact resistance that cause momentary current overload of G that has very high sensitivity (in μA). If R_2 was used as a variable resistor, the measurement would be significantly more difficult due to the mechanical properties of the variable resistor.

The Wheatstone bridge measurement process in an industrial-grade automated system is done in the following way: the microcontroller (MC) changes dozens of R_2 resistance values while measuring voltage U_{DB} on the bridge. This voltage is converted by an A/D converter (ADC) into a digital signal for MC. Using the method of successive approximations, the correct value of R_2 is found when the bridge response is near the zero level (i.e. bridge is in the balance). It is necessary to ensure that the ADC can read very small voltage changes, which is only possible with high-resolution $\Sigma\text{-}\Delta$ ADC. The price of the whole system would significantly exceed the budget limit defined for the project, if expensive $\Sigma\text{-}\Delta$ ADCs were used.

Fig. 4 shows the standard 2-wire U/I method of resistance R_x measurement, integrated into a digital multimeter (DMM), [6]. The current source (CS) in the instrument generates a constant current that passes through the measured resistor, creating a voltage drop U_x measured by the digital voltmeter (V) in the instrument itself. This voltage drop is proportional to the measured resistance R_x [9].

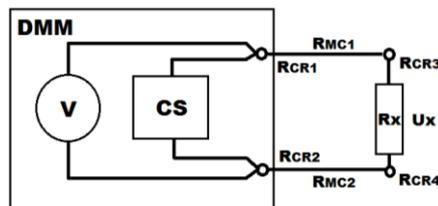


Fig. 4 Block diagram of resistance measurement with standard 2-wire U/I method using DMM

The problem of lower grade class of multimeters is that the minimum resistance measurement range is usually 200 Ω .

It is a regular practice with technical staff and novice engineers that 2-wire method is used, regardless of the resistance measured and available measurement ranges. This is a common mistake due to the lack of formal education in metrology, inexperience in the field and especially bad practices that continue to be implemented due to the human factor.

One of the main characteristics of a DMM is number of digits and number of counts of its display resolution. The cheapest and most commonly used are 3 $\frac{1}{2}$ digits instruments, while 3 $\frac{3}{4}$, 3 $\frac{5}{6}$, 4 $\frac{1}{2}$, 4 $\frac{3}{4}$, 6 $\frac{1}{2}$, etc. digits are also commercially available. The number of counts can be determined from the number of digits, e.g. a 3 $\frac{1}{2}$ digits multimeter can display 3 full digits. The $\frac{1}{2}$ indicates that the most significant digit has the maximum value of 1 (out of 2) that can be displayed. The maximum value that can be displayed on this multimeter is 1999. With the zero count counted in, we say that there are 2000 counts in total. In the same way, the number of counts for other multimeters is determined: for 3 $\frac{3}{4}$ - 4000, for 3 $\frac{5}{6}$ - 6000, for 4 $\frac{1}{2}$ - 20000, etc. With an increase in resolution, i.e. the number of counts, the price of a multimeter increases also.

The resolution of a DMM can be determined by dividing the measurement range value with the number of counts. Since the low-ohm measurements are carried out in the lowest range, for the 3 $\frac{1}{2}$ digits instrument, this means resolution of 100 m Ω , and 10 m Ω for 4 $\frac{1}{2}$ digits, which is insufficient to measure (20 \pm 0.1) m Ω . Only with a 6 $\frac{1}{2}$ digits it is possible to achieve the 100 $\mu\Omega$ resolution, but the price of such instruments exceed the projected budget. Also, the resistance measurement error of such instruments is 0.5 % - 5 %, depending on the measurement range, thus they are completely inadequate for the purposes of direct measurement of a high-precision shunt.

If a more expensive laboratory-class instrument with adequate measurement characteristics would be used, the problem of instrument thermal overload would arise due to the longer measurement periods with high CS current [13]. Milliohm resistance is, effectively, a short circuit for any instrument, which in this case measures in the lowest ohms range with the highest available current of the current source. If this current is small (at the order of mA), it produces voltage drop on the shunt (in μV), too small for the instrument to measure.

For a milliohm-meter current source in mA or A range [5], there is always a time limit given by the manufacturer that the maximum measurement time is 10 to 30 seconds [8]. A large CS current creates high thermal dissipation within the instrument case, inevitably leading to thermal overload of the device and its failure.

In addition, when the current flows through the resistor, its resistance changes due to the temperature increase. For a copper alloy conductor, with resistance of 20 m Ω at a 20 $^{\circ}\text{C}$, when exposed to 50 $^{\circ}\text{C}$ its resistance changes for 242.46 $\mu\Omega$, exceeding the error limit. Therefore, it is necessary to avoid large temperature changes in order to maintain the resistance value within the given limits.

For the above reasons, the maximum recommended current for measuring resistance is 100 mA [14]. This option is not available in most mid-range multimeters powered by regular batteries that limit maximum CS current. Continuous use of such instruments on the lowest resistance measurement range, results in only several hours of autonomous work on standard batteries. Frequent replacement of batteries would quickly result in a significant increase of the total cost of the device.

The standard method for measuring resistance in modern instruments is the *ratiometric method*, [14] and [15]. While regular absolute (direct) measurements are simpler (such as U/I method), the ratiometric method, on the other hand, performs two (or an even number) of measurements, and the desired value can be calculated based on the ratio of those measurements. Most often, one value is taken as a reference, in relation to which the second value is measured. The advantage of this method is that the measured values mutually depend on each other, so the change in one value automatically reflects on the other value, while their ratio remains unchanged. In this way, the potential sources of error such as humidity, temperature, pressure etc. are eliminated using just calculation.

In this method, the reference resistor of a known value and the unknown resistor (with order of magnitude of the reference resistor) are connected in series and form a voltage divider of known input voltage across them. A precision voltmeter measures voltage drop on each resistor and the voltage ratio is compared with the resistance ratio, a method shown to have greater accuracy than a direct measurement of resistance with the conventional U/I method, [14].

The problem with this method occurs when measuring low resistances, where for the series connection of two 20 m Ω resistors, voltage source of 1 V has to produce the current of 25 A, which could endanger safety of the user. Such a source would be expensive, but also with the power dissipation of 12.5 W, it would burn out a low-power resistor.

The finite resistance of the test leads connecting shunt to the multimeter [15] introduces an additional error in measurement. This resistance can be of the same magnitude as shunt resistance, but also up to ten times higher, if low-quality test leads are used. When measuring low resistances, intermittent contacts increase the error, mainly cable to shunt connections and instrument input connectors, as in Fig. 4. The total resistance of the test leads and contact resistances can be up to 1 Ω , which is unacceptable for this type of measurements. Even with high-grade instruments such as Fluke 87V [16], test leads resistance is about 100 m Ω – five times larger than the shunt resistance. This problem is usually resolved by so-called relative "zeroing": the ends of test leads are shorted together and the instrument is adjusted to display zero reading. The measured test leads resistance is stored in memory and simply subtracted from every consequent measurement, [17]. This solves the problem only to a certain degree, as the resistance of the test leads and contacts varies over time – it changes with current, physical position, temperature, etc. Hence, the "zeroing" is also inadequate for precise $\mu\Omega$ measurements [6], as contact resistance changes even with minor shifting of the contacts by the user. During the manual shunt processing stage (filing and cutting), operator exerts mechanical pressure on the shunt, creating significant vibrations and stress to the resistive material that instantly change the resistance of the contacts, with each attempt to process the material. Regular and periodic "zeroing" of the test leads would be required, complicating the device design, and affecting its price and measurement time.

The problem with wide range variation of ambient temperature in an industrial environment is always present, affecting resistors and current sources (CS are used in temperature sensors very often due to their temperature sensitivity), lowering the measurement accuracy, [14]. A typical current source error is 0.01 %/°C. Temperature variation of ± 5 °C would make this source too unstable for low resistance measurement.

4. DESCRIPTION OF THE OPTIMAL SOLUTION

After analyzing all known problems and limitations, it was decided to create a composite milliohm-meter (Com-mOhm), made up of several separate modules, based on the Kelvin (four-wire) version of the standard U/I method for resistance measurement, as shown in Fig. 5. This example is well known in the measurement theory: the current source dictates the current I_{CS} through the resistor, and corresponding voltage drop U_X is measured with voltmeter V. The value of the measured resistance R_X is obtained as:

$$R_X = \frac{U_X}{I_{CS}} \quad (2)$$

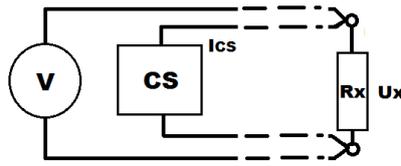


Fig. 5 Kelvin's four-wire method of measuring resistance

The most important condition in this method is to use two pairs of cables (four wires) – a voltage pair (for voltmeter) and a current pair (for current source), with current and voltage terminals connected directly at the ends of R_X , in order to eliminate the influence of finite cable and contact resistances. The current through resistor R_X is calculated from the current divider equation:

$$I_X = \frac{R_V}{R_X + R_V} I_{CS}, \quad (3)$$

where R_V represents the input resistance of the voltmeter (multimeter).

Input resistance of DMM depends on the ADC within the instrument and resistance of the measurement range voltage divider. The cheapest digital 3 1/2 digits multimeters, based on ICL7106 or similar ADC, have input resistance of 1 – 10 M Ω . Higher-grade instruments have 10 – 100 M Ω input resistance, with the lowest voltage range ranging up to several G Ω . The lowest measurement range of these instruments is usually the *basic voltage range*, where the multimeter input is connected directly to the ADC input with G Ω input resistance. This high input resistance of a DMM results in minor bias current flowing into the instrument. For the current source of 100 mA, the multimeter bias current is in pA range, not affecting measurement results.

If a pair of cables with cross-sections of 0.5 mm² and 1 m of length were used for the measurement, the resistance would be about 72 m Ω , much higher than 20 m Ω shunt resistance. In most practical cases, real resistance being measured with this method is R_m , as in (4) – R_X with added sum of all resistances of test leads (R_{MCi}) and sum of all contact resistances (R_{CRj}).

$$R_m = R_X + \sum_i R_{MCi} + \sum_j R_{CRj} \quad (4)$$

The advantage of the Kelvin method is that very long connecting cables can be used, (5-10 meters, or even more), which is a common case for an industrial setting, [6] and [9]. The main problems of this approach are:

1. A current source of 100 mA with stability (precision) of 0.05 % is needed. This level of precision is only available in integrated current sources, with output range of 100 μ A to 10 mA, [14]. Most of the integrated current sources over 10 mA have at least ± 1 % error, such as REF200 [18] and LM334 [19] made by Texas Instruments.
2. The current of 100 mA produces only 2 mV at 20 m Ω resistance. In order to achieve the desired accuracy and precision, an instrument capable of reading 2 mV ± 0.05 %, i.e. with 1 μ V resolution, must be used.
3. The best instrument that could be obtained for this purpose was Uni-T UT61E [20] with resolution of 4 $\frac{1}{2}$ digits (maximum display of 22000 counts). The lowest voltage dc range of this multimeter is 220 mV, with resolution of 10 μ V – 10 times worse than needed.

The optimal solution was found in the modification of Kelvin 4-wire method in the form of composite milliohm-meter (Com-mOhm), as seen in Fig. 6.

The current source uses double servo loop. A servo-loop represents a system in which the adjustment of its parts is automatically made to get the response within certain limits. In this case, one servo-loop is made with U2 operating amplifier that corrects the level of GND voltage for the precision reference U1, depending on the monitored current at the output of the current source. The other servo-loop with U3 ensures temperature stability of the current source that is set to $I_{ref} = 100$ mA. For $R_X = 20$ m Ω shunt with tolerance of $\Delta R_X/R_X = 0.5$ %, it is possible to determine maximum variation of U_X voltage measured with voltmeter V:

$$U_X = 100 \text{ mA} \cdot (20 \text{ m}\Omega \pm \Delta R_X) = 2 \text{ mV} \pm (100 \text{ mA} \cdot 0.1 \text{ m}\Omega) = 2 \text{ mV} \pm 10 \mu\text{V} \quad (5)$$

The maximum variation of the shunt resistance corresponds to the smallest quant (resolution) of dc voltage reading of the UT61E. Declared multimeter error in this measurement range is expressed as 0.1 % of reading + 5 digits. This equals to the error of 52 μ V for 20 mV reading, rendering it impossible to measure 10 μ V of voltage change.

However, it was found that the UT61E actually possesses sensitivity of 10 μ V, in form of having the last figure on the display accurately changing in these increments. This was verified by changing the calibrator standard voltage in 10 μ V steps, observing UT61E display and checking it against the Fluke 8846A multimeter.

This allowed the optimal solution to be found in the form of relative measurements of the transmission standard, according to the principles given in [4], [9], [10] and [21].

A prototype of the shunt standard R_0 was made, with its resistance adjusted to 20 m Ω ± 10 $\mu\Omega$ using the Fluke 8846A. This standard then serves to determine what voltage UT61E shows as reference (U_{Vref}) when the resistance of the shunt is "exactly" 20 m Ω .

When UT61E is used in Com-mOhm, for shunt resistance change of ± 0.1 m Ω , reading change of ± 1 digit is obtained, (i.e. $U_{Vref} \pm 10$ μ V) in relation to the value obtained for R_0 .

It can be concluded that the multimeter here serves only as an *indicator*, indicating whether the measured resistance is or is not within tolerance limits. If it is, its value cannot be accurately determined. This represents sufficient functionality of the instrument for the required task, at the lowest price. Also, it is simple enough to be handled by the untrained technical personnel in the production, making it the best possible solution for the given problem.

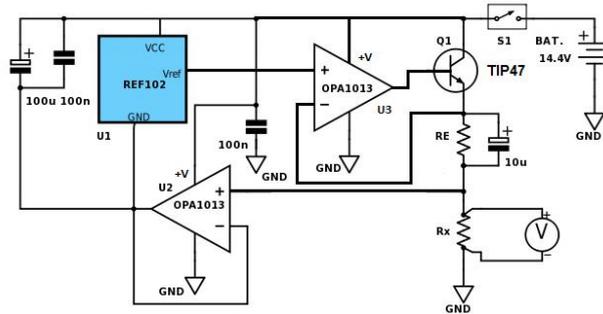


Fig. 6 Composite milliohm-meter (Com-mOhm) scheme

5. PRACTICAL REALIZATION

During the design process of Com-mOhm, various design inputs from [14], [15], [22], [23], [24], [25] and [26] were used.

Fully functional Com-mOhm is given in Fig. 6. Its main block is the current source with U1 - precise voltage reference REF102 [24] with voltage output of $10\text{ V} \pm 2.5\text{ mV}$, temperature coefficient of $2.5\text{ ppm}/^\circ\text{C}$ that ensures negligible change in current, even at large external temperature fluctuations that are typical for the industrial environment. The precision reference allows single supply voltage from 11.4 V to 36 V , enabling battery-powered operation. Its low drift and high stability output is impervious to large input voltage swings. In addition, its long-time stability is estimated at $5\text{ }\mu\text{V}$ over 1000 hours of work.

The output voltage is passed to operational amplifier U3 and transistor Q1, which serves as current amplifier in active mode, [22] and [23], since the voltage reference has maximum output current of only 10 mA . From the Q1 emitter, a 100 % feedback of dc voltage is applied back to the inverting input of U3. Since the non-inverting input of U3 is at V_{ref} potential, knowing that operational amplifier always forces its "+" and "-" inputs to be at the equal voltage levels, it is clear that the voltage at the Q1 emitter will be V_{ref} . This eliminates the voltage variation of the transistor base-emitter V_{BE} voltage due to temperature change, a prerequisite for stable current amplification. V_{BE} variation affects base and collector currents, as well as current through the R_{E} , resulting in large measurement error. Temperature coefficient of V_{BE} is $-2\text{ mV}/^\circ\text{C}$.

Q1 is a standard power NPN transistor TIP47 [27], rated 40 W with maximum current of 1 A , in TO-220 package, which can be easily mounted on a metal heat sink, if necessary.

Proper selection of operating amplifiers U2 and U3 is one of the most critical aspects of the entire system. OPA1013 was chosen, with its small offset voltage drift, typically around $0.5\text{ }\mu\text{V}$, providing stability of the current source. Another important factor is its low input bias current, around 10 nA , providing that current through R_{E} is identical to the current through the measured resistor R_{X} . The temperature coefficient is $2.5\text{ }\mu\text{V}/^\circ\text{C}$, which allows stable operation in wide range of temperatures.

U2 (OPA1013) is configured as voltage buffer, forcing voltage on GND reference pin to be the same as the voltage across R_X (voltage between the non-inverting U2 input and ground), [25] and [26]. As the result, I_{ref} current through the R_X is constant and defined as:

$$I_{ref} = V_{ref} / R_E \quad (6)$$

V_{ref} is the reference output voltage and R_E is emitter resistor, adjusted to obtain the correct current. Sudden change in the resistance of R_X or R_E , results in sudden change of the voltage value at the U2 "+" input due to the flow of constant current I_{ref} :

$$V_+ = I_{ref} \cdot R_X \quad (7)$$

While the first servo-loop has full feedback that ensures temperature stability of Q1 current amplifier, the second servo-loop provides constant current through the R_E , regardless of the R_X value. The second servo-loop in feedback line, also in the form of voltage buffer, manages the potential of the GND input of the voltage reference, thus controlling the output voltage. We can say that the current source is stabilized with two separate feedbacks, in order to compensate for two different sources of error. If the voltage at the "+" input of U2 increases or decreases, the potential of the GND input of the voltage reference will also increase or decrease. The voltage reference ensures that the potential difference between its output and the GND pin is constant at 10 V. This ensures that the voltage across the R_E is also exactly 10 V, regardless of the voltage drop on the R_X . This results in the effect of a "floating" voltage, relative to the battery ground potential, but constant at the ends of the R_E . The voltage on the resistor R_E remains unchanged, resulting in 100 mA constant current source, dependent only on the value of precision resistor R_E . The accuracy of current source is directly related to R_E accuracy, and its stability (precision) relates to the temperature stability of R_E .

The value of resistor R_E is calculated from (6) as the ratio of voltage reference $V_{ref} = 10$ V and constant current $I_{ref} = 100$ mA. The nominal value of the resistor R_E is 100 Ω . The constant current of 100 mA generates thermal dissipation of 1 W at the resistor. This amount of heat inevitably leads to the effect of self-heating and resistance change [3], affecting shunt resistance for at least one order of magnitude more than environment temperature change.

In order to preserve the stability of the current reference, R_E is constructed as a composite resistor standard, described in [3], reducing self-heating resistance change to zero. Metal-film resistors $R_{nMF} = 400$ Ω were selected (serial connection of two resistors $R_{nMF1} = R_{nMF2} = 200$ Ω) and carbon resistors $R_{nCF} = 200$ Ω , connected according to the equivalent scheme in Fig. 7, as a substitute for R_E , [3]. Opposite temperature coefficients of metal-film and carbon resistors provide temperature stability of the current source, eliminating the self-heating effect. R_1 and R_2 are selected high-resistance resistors for precision adjustments of the source current to (100 ± 0.05) mA.

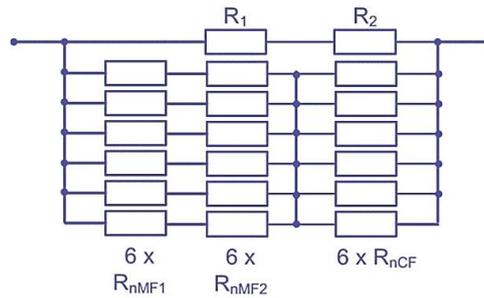


Fig. 7 Composite resistor standard R_E , equivalent connection scheme

100 μF and 100 nF capacitors in the circuit provide voltage stabilization and filtering. Additional stabilization of the R_E voltage is achieved by the electrolytic 10 μF capacitor. A tantalum capacitor is used, with equivalent serial resistance (ESR) 10-50 times lower than a conventional aluminum electrolytic capacitor of the same capacitance (around 0.2 Ω). Tantalum capacitors are thermally stable with low leakage current.

The current source is a milliohm-meter component must have its own dedicated power source, which should provide stable voltage (over 12 V), required for the stable operation of REF102. In addition, this power source has to provide 120 mA (for current source and associated components) during at least 16 hours (two shifts in one working day). The switch S1 turns on and off the battery power.

Table 1 Comparison of multimeter characteristics

Characteristics	UT61E	Fluke 8846A
Number of digits	4 ½	6 ½
Number of counts	22000	1000000
Input impedance ($G\Omega$)	3	10
The lowest DC voltage range (mV)	220	100
Voltage resolution at the lowest range (μV)	10	0.1
Price (EUR)	60	1500

A spare Siemens laptop battery is used as the main power source. The battery is composed of eight rechargeable lithium-ion cells, with voltage of 14.4 V and a capacity of 4400 mAh – around two times more than the Com-mOhm needs. The battery is similar in size to the UT61E multimeter, which makes Com-mOhm compact and easy to operate and transport. The second component of the Com-mOhm, the UT61E multimeter, has its own battery supply.

Com-mOhm was adjusted and calibrated in the Laboratory for Metrology. The current source is set to (100 ± 0.05) mA by trimming R_E . Measurements with the Fluke 8846A confirmed the accuracy and stability of the current source below ± 1 μA . The precision shunt standard R_0 was also adjusted and calibrated.

A comparison of the Uni-T UT61E and the Fluke 8846A characteristics is given in Table 1.

6. MEASUREMENT RESULTS

Com-mOhm was installed and used in the factory hall where the first set of 16 shunts was produced. The hall temperature was 5 °C higher than the temperature in the reference laboratory.

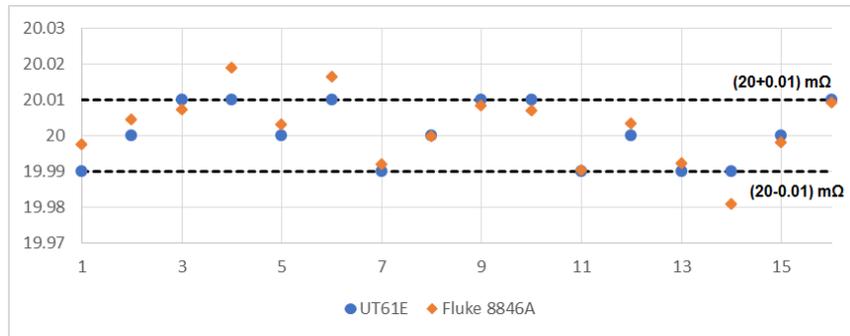


Fig. 8 Graphical comparison of measurement results

Table 2 Overview of the measurement results

R_x	R_{m1}	R_{m2}	$ R_{m1}-R_{m2} $	$\frac{ R_{m1}-R_{m2} }{R_{m2}} \cdot 100$
#	mΩ	mΩ	μΩ	%
1	19.99	19.9976	7.6	0.0380
2	20.00	20.0045	4.5	0.0225
3	20.01	20.0073	2.7	0.0135
4	20.01	20.0191	9.1	0.0455
5	20.00	20.0031	3.1	0.0155
6	20.01	20.0165	6.5	0.0325
7	19.99	19.9919	1.9	0.0095
8	20.00	19.9998	0.2	0.0010
9	20.01	20.0084	1.6	0.0080
10	20.01	20.0069	3.1	0.0155
11	19.99	19.9902	0.2	0.0010
12	20.00	20.0035	3.5	0.0175
13	19.99	19.9922	2.2	0.0110
14	19.99	19.9807	9.3	0.0465
15	20.00	19.9981	1.9	0.0095
16	20.01	20.0092	0.8	0.0040

All the manufactured shunts were subsequently moved to the laboratory, where they were calibrated after 24 hours of stabilization.

The results of field measurements using the UT61E (R_{m1}) and the laboratory measurements with Fluke 8846A (R_{m2}) are given in Table 2. The absolute value of the absolute measurement error is determined as the difference of readings between Com-mOhm and Fluke 8846A. The absolute value of the relative error is also given.

The standard deviation for the 16 shunts of the first production series is 9.64 μΩ.

Fig. 8 shows graphical representation of the measurement results with the upper ($20 \text{ m}\Omega + 10 \text{ }\mu\Omega$) and the lower ($20 \text{ m}\Omega - 10 \text{ }\mu\Omega$) range of allowed values.

The results seem to agree well, only R4, R6 and R14 are outside the required range. These small discrepancies can be attributed to the change in the copper alloy resistance due to the difference in the temperature of the factory hall and the laboratory, and to the measurement error of the laboratory multimeter.

6. THE ASSESSMENT OF THE MEASUREMENT UNCERTAINTY

Shunt resistor measurement is carried out in two steps [28], as in Fig. 9. In the first step, a standard shunt R_0 is placed instead R_X and the voltage drop U_0 is measured. In the second step, shunt under test R_X is placed instead R_0 and voltage drop U_X is measured. Based on these two measurements, the value of the shunt under test is calculated. Current I_0 is calculated from the first measurement with the shunt standard R_0 :

$$I_0 = U_0 / R_0 \quad (8)$$

After adding correction, (8) becomes:

$$I_0 = \frac{U_0 + \delta U_0 + \Delta U_0 + \Delta U_0 \text{Stab}}{R_0 + \Delta R_0} \quad (9)$$

In the step two, resistance of the shunt under test R_X is calculated:

$$R_X = U_X / I_X \quad (10)$$

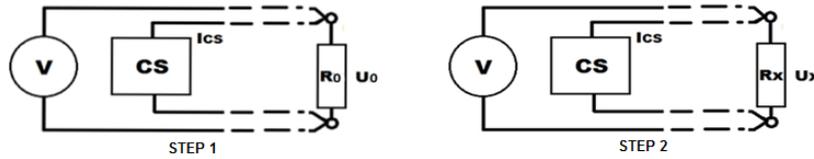


Fig. 9 Two-step shunt measurement

Current I_X can be represented as a sum of current I_0 and correction $I_0 \text{Stab}$ due to I_0 instability:

$$R_X = \frac{U_X}{I_0 + I_0 \text{Stab}} \quad (11)$$

Mathematical model of the measurement result is obtained by combining (9) and (10), in according to GUM [29]:

$$R_X = \frac{\Delta U_0 + \Delta U_0 \text{Stab} + U_X + \delta U_X}{I_0 \text{Stab} + \frac{U_0 + \delta U_0 + \Delta U_0}{R_0 + \Delta R_0}} \quad (12)$$

Used notation: U_x - mean value of U_x , δU_x - measurement result U_x correction due to finite voltmeter resolution, $\Delta U_{0\text{Stab}}$ - measurement result correction due to instability of measurement of U_0 , U_0 - mean value of U_0 , δU_0 - measurement result U_0 correction due to finite voltmeter resolution, ΔU_0 - measurement result U_0 correction due to inaccuracy of measurement, R_0 - resistance of the standard shunt R_0 , ΔR_0 - measurement result correction due to inaccuracy of shunt R_0 , $I_{0\text{Stab}}$ - measurement result correction due to instability of current I_0 , I - measured current.

Measurement uncertainty budget is given in Table 3.

Table 3 Com-mOhm measurement uncertainty budget

Symbol	Estimate	Standard uncertainty	Type	Distribution	Sensitivity	Contribution to measurement uncertainty
U_x	2.01×10^{-3}	6.32×10^{-6}	A	Normal	10	63.2×10^{-6}
δU_x	0	2.89×10^{-6}	B	Uniform	10	28.9×10^{-6}
$\Delta U_{0\text{Stab}}$	0	127×10^{-9}	B	Uniform	10	1.3×10^{-6}
U_0	2×10^{-3}	6.32×10^{-6}	A	Normal	-10.1	63.6×10^{-6}
δU_0	0	2.89×10^{-6}	B	Uniform	-10.1	29×10^{-6}
ΔU_0	0	12.7×10^{-6}	B	Uniform	-50×10^{-3}	635×10^{-9}
R_0	20×10^{-3}	0	B	Uniform	1.01	0
ΔR_0	0	11.5×10^{-6}	B	Uniform	1.01	11.6×10^{-6}
$I_{0\text{Stab}}$	0	28.9×10^{-6}	B	Uniform	-201×10^{-3}	5.8×10^{-6}
R_x	0.0201					99.4×10^{-6}
Extended measurement uncertainty with coverage factor $k=1$: $\pm 0.000099 \Omega$						
Extended measurement uncertainty with coverage factor $k=2$: $\pm 0.00020 \Omega$						

8. CONCLUSION

The realized composite milliohm-meter system (Com-mOhm) meets the requirements of stability, accuracy, reliability and low price. The set of hardware components (multimeter, current source and shunt standard) cost about \$100, about 20 times less (not including procedures like calibration, adjustments, circuit design, etc.) than a commercial laboratory-grade instrument. The measurement results in the field and laboratory are sufficiently consistent for the stated requirements.

A solution of a specific industrial problem, with numerous constraints, is presented. Careful analysis of the problem, examination of all influential parameters, the optimal design of the electronic circuit and the knowledge of how all the relevant blocks of the system function, provide non-standard solution for a specific problem with favorable benefit/cost ratio. The core electrical engineering knowledge is fundamental for bridging the gap between theory and practice, especially in regular industrial environment applications, where both innovative and old (but well-tested) technologies are used in conjunction. In present volatile economics, current and "obsolete" technologies, that provide backbone of existing industry, might become very important to be maintained, repaired and improved in order for a company to remain with cost-effective product lines.

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