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Functional Characteristics of a Resistance Comparator and a Practical Way of their Improvement

Abstract. *The authors designed and realized an instrument for resistance measuring using the known comparison method. As the first solution it was a single range unit for small resistors. The further investigations had a goal to reach a wide resistance range measuring. It was achieved, but some of appeared difficulties had to be overcome. The paper presents the real instrument characteristics and describes the way of practical solutions of their improvements.*

Streszczenie. *Autorzy zaprojektowali przyrząd do pomiaru rezystancji bazujący na metodzie porównania. Abu osiągnąć szeroki zakres pomiarowy niezbędne było rozwiązanie wielu nowych problemów. W artykule zaprezentowano możliwości wykonanego przyrządu. (**Charakterystyka funkcjonalna komparatora rezystancji oraz możliwości poprawy jego parametrów**)*

Keywords: Resistance comparator, parasitic voltage, output voltage hold circuit, response time, measuring current.
Słowa kluczowe: komparator rezystancji, czas odpowiedzi, prąd pomiarowy.

Introduction

The Resistance Comparator is a very precise instrument for resistance measuring. The instrument was designed and realized for the purpose of the new materials and alloys electrical characteristics examination in a laboratory of Mining and Metallurgy Institute Bor, Fig 1 [1].

Fig.1. Front panel of the realized instrument

The solution called the Kelvin, or 4-wire, resistance measurement method is often used for small resistance measurement. It involves the use of an ammeter and voltmeter, determining specimen resistance by Ohm's Law calculation. A current is passed through the unknown resistance and measured. The voltage dropped across the resistance is measured by the voltmeter, and resistance calculated using Ohm's Law ($R=U/I$). Very small resistances may be measured by using large current, providing a more easily measured voltage drop. The high measuring current causes the resistor hitting, and than occur some additional problems. However, it is not the subject of the paper.

The realized electronic chopper stabilized resistance comparator uses an often applied method based on comparison the voltages at the ends on measured resistor with reference one [2]. The same measuring current is passed through both resistors, and the voltages are amplified by the same three stage gain amplifier, Fig. 2. It is realized in a form of prototype and consists of two separated comparators for two measuring ranges:

- Low resistances (10 mΩ to 100 Ω) and
- High resistances (1 kΩ to 1 GΩ).

The instrument functions in low resistance measuring mode are realized on the next way.

The current circuit module (Fig. 2) consists of a source of measuring current which supplies both serial connected resistors, the reference one (R_R) and unknown resistance (R_X). Measuring cycle is divided into two periods. The current is switched on and off a couple of times in a first time period of the measuring cycle. In those intervals the parasitic voltages are measured, nulling intervals in Fig 3. The rhythm of switching is dictated by control circuit logic. While the measuring current is established, the voltage changes at the resistors terminations are measured, measuring intervals in Fig 3. The final result is obtained by the subtraction of previous measured parasitic voltages values. It is known as the annulling process.

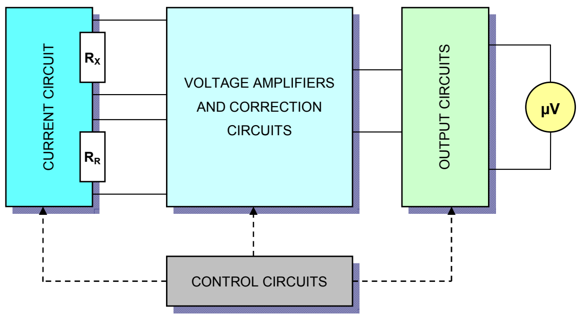

Fig.2. Overall block diagram of chopper stabilized comparator graph.

The voltage amplifying circuit module is realized as a triple amplifiers chain with great amplifying rate and very good linearity. Principle of time multiplexing allows the voltage at both resistors (reference and measured one) to be amplified by the same amplifiers. It eliminates the measuring errors caused by amplifier elements. The same module contains the correction circuits designed to suppress many unwanted influences.

The function of output circuits is to hold the clean amplified voltage until the next measuring cycle occurs, it means 0.2 sec.

The control circuit module is designed to control all steps of measuring process and comparator functions. It performs it generating the sequence control signals, Fig. 3. Those signals switch on and off many switches executing the measuring steps in a correct way.

Providing the same measuring current through both resistors and using the same amplifiers for voltages to be comparing, eliminates the most of measuring error sources.

The unknown (measured) resistance can be calculated as the rate of voltages at the ends of resistors R_R and R_X, Fig. 2:

(1) $$R_X = R_R \frac{U_X}{U_R}.$$

The above expression is simple theoretically, bat there are many sources of unwanted influences and disturbances in practice, making the results worse.

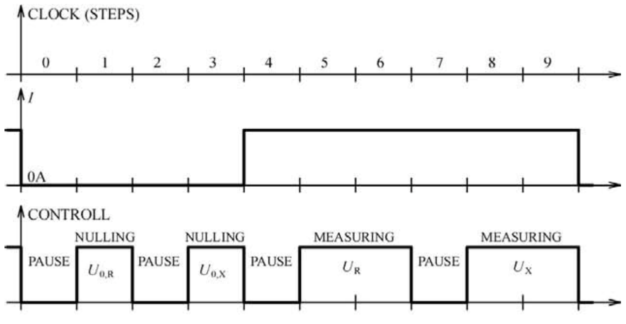

Fig.3. The main control signals graph.

Parasitic direct current (DC) and alternative current (AC) voltages are the main sources of measuring errors in chopper stabilized resistance comparator prototype.

The practical usage of a realized instrument prototype shows one more disadvantage: the time until the final i.e. correct result appears at the display is to long (bad instrument response time [3]). It means that the stationary state establishing sequence should be shorter.

In the next chapters those problems and their overcoming are described in more details.

Parasitic Voltages and the Way of Their Decreasing

In the measuring (input) voltage there is present the DC parasitic voltage component (for instance: thermo-voltages with value of a few tenth of 1 μV and operational amplifier offset voltages also), and an AC component (50 Hz) as well. Because there is an intention to measure with resolution of 0,01 μV, it is to big parasitic voltage value and can considerably degrade the accuracy of high resistance measurements.

The measuring process is completed in ten steps [1]. Two of them are used for input parasitic voltage annulment: one for R_R and other for R_X. A controller, based on a decade (Johnson) counter, controls all of analog switches. It is driven by network supply frequency signal (50 Hz), one step is 20 ms, and the measuring cycle (ten steps) takes 200 ms, Fig 3. It provides rate of 5 measurements in a second.

By design and development the unit with fixed measuring range, there is a possibility to choose the components to eliminate the parasitic voltages using standard correction circuit. But there is not the same case if the multirange instrument is in a question. It is necessary to apply a modified annulated electrical circuit, to eliminate all voltages in output signal, which are not the result of current flow through the resistors R_R and R_X. The dominant parasitic voltage comes from operational amplifiers input voltages offset and it could reach one hundred μV.

The DC parasitic voltage correction does not depend of controller clock frequency [3]. But the dominant role of AC disturbances has the influence of power network (50 Hz). That's why the controller clock is synchronized to the network frequency. It turned out that the effect of that circuit and a sample and hold output circuits as well, is very much dependent of the phase difference between controller clock and network voltage frequency [4]. For fixed amplifying (single range mode) it is possible to overcome the problem by the appropriate choosing and adjustment of elements [1]. For the instrument with many measuring ranges, the measuring currents are different for any range and the amplifying rates also. It is more difficult to decrease the unwanted influence of parasitic voltages in that case [4].

To overcome the problem, the new, modified correction circuit is designed, Fig. 4. The new annulment circuit encircles the offset voltages of that circuit, and of all previous amplifying stages, as well.

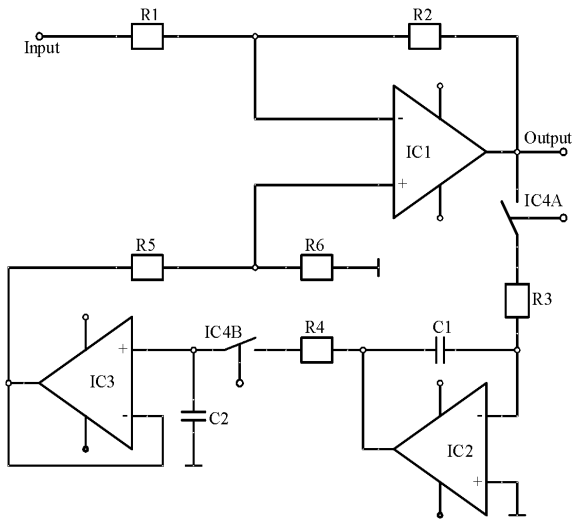

Fig.4. The schema of improved correction circuit.

The necessary amplifying level is reached in previous stages (not shown in Fig. 4). The circuit IC1 with resistors R_1 and R_2 is an output amplifier for measuring voltages with amplifying equal to -1. Its offset voltage is encircled by correction and not critical. Because of necessary high linearity, it has great amplifying rate (open loop gain [5]). The chopper stabilized integrated circuit IC2 together with R_3 and C_1 runs as an integrator and generates correction voltage. While annulling phase the analog switch IC4A is on and IC4B off. There is no the measuring current in that period and the correction voltage at the output of IC2 equals just to parasitic voltage. In the next phase the switch IC4A goes off and IC4B on and the correction voltage is lead via C_2 in the adequate proportion to IC1 input. After this (first) step the parasitic voltage at the IC1 output is significant lower. The same process can be repeated to annul the parasitic voltage. Assume that is an initial state and the capacitor C_1 is discharged (U_{INT0} = 0), after first integration period the IC2 output voltage is:

(2) $$U_{Out1} = -\frac{1}{C_1 R_3}\int_0^T U_{Out0}\,dt = -\frac{U_{Out0}T}{C_1 R_3},$$

where T is the integration time (the duration of one controller step, 20 ms).

At the next step the switch IC4A goes off and IC4B on, and the capacitor C_2 is charging. To reach the full capacitor charging, the time constant R_4C_2 has to be as small as possible. At the same step of measuring cycle the same voltage moves to the input of IC1 amplifier (via R_5 and R_6) as a correction and the resultant parasitic voltage (U_{Out1}) in the next step is:

(3) $$U_{Out1} = U_{Out0} - \frac{U_{Out0}T}{C_1 R_3}\frac{R_2}{R_1}\frac{R_6}{R_5 + R_6}.$$

To prevent the fast voltage decreasing, the ratio R_5/R_6 has to be high (R_5/R_6>100). Now the expression (3) becomes:

$$U_{Out1} \approx U_{Out0}\left(1-\frac{T}{C_1R_3}\frac{R_2}{R_1}\frac{R_6}{R_5}\right). \tag{4}$$

and after k annulment steps the output voltage can be present as:

$$U_{Outk} \approx U_{Out0}\left(1-\frac{T}{C_1R_3}\frac{R_2}{R_1}\frac{R_6}{R_5}\right)^k. \tag{5}$$

For previous value to be zero, the next relation has to be satisfied:

$$1-\frac{T}{C_1R_3}\frac{R_2}{R_1}\frac{R_6}{R_5}=0. \tag{6}$$

Practically, there is a need to make more cycles to achieve desired low parasitic voltage value. It means that the electric circuit shown in Fig. 4 could do so fast parasitic voltages annulment, independent of voltage amplifying.

The realized circuit has shown impressive results: in the worse case (the lowest measuring range of 20 mΩ and amplifying of 1000) the starting parasitic voltage was 100 mV. After first annulment cycle it drops below 5 mV and at next step, below the scope sensitivity level.

By equalization the controller clock duration with the time period of network frequency (20 ms), the integral of that voltage becomes zero and the unwonted influence of power network (AC disturbances) is eliminated [6, 7].

The Ramp-up Time and Reduction of Its Duration

The transitional phase is the time interval between the switching on the instrument (measuring start) and the result appearing. Sometimes it is called rump up time, or stationary state achievement.

The instrument measuring cycle consists of 10 steps, Fig. 3. The time of presence for both input voltages (U_R i U_X) is 40 ms each, followed by 160 ms of pause [7, 8].

Because of capacitor discharging in a time and as a consequence of current leaking occurring, the measuring voltage is decreasing while the measuring time. To make those changes as small as possible, the great capacitor is needed. In the original solution (Fig. 1) the big input resistance is used to avoid the AC disturbances. Those conditions give the long time constant, and the slow stationary state achievement. The charge injection effect makes the instrument performances worse as well [9]. The long instrument response time could be considered as its consequence also.

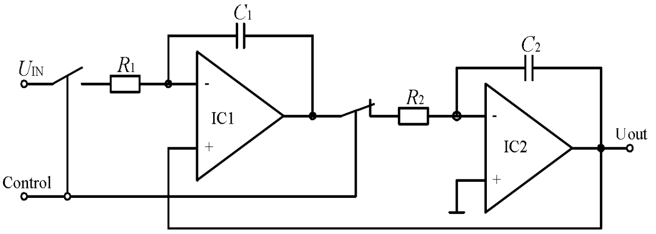

Fig.5. The new output voltage hold circuit.

To overcome those problems the redesign of output voltage hold circuit is done, Fig. 5. The circuit operates at the next way:

At the start time the capacitors are discharged (initial state). In first measuring interval, the output voltage of IC1 equals to the IC2 offset voltage, $U_{Offset2}$, Fig. 5.

At the end of integration time period the input voltage at capacitor C_1 reaches value of:

$$U_{Int1} = -\frac{1}{R_1C_1}\int_0^{2T}(U_{IN}-U_{offset2})dt = -\frac{2T}{R_1C_1}(U_{IN}-U_{offset2})\cdot \tag{7}$$

T=20 ms is integration period (one step of measuring cycle, Fig 4) [7]. After integration finish, the switches change the own states. Now the second operational amplifier (OA) runs as an integrator and raises its voltage until the output voltage of first integrator becomes equal to the input offset voltage of second OA, $U_{offset2}$. The output voltage of the second integrator equals – U_{Out1}.

$$U_{Out1} = -U_{Int1} + U_{offset2}\,. \tag{8}$$

The expressions (7) and (8) give the next relation:

$$U_{Out1} = \frac{2T}{R_1C_1}U_{IN} + (1-\frac{2T}{R_1C_1})U_{offset2}\,. \tag{9}$$

If the resistor and capacitor values satisfy equitation R_1C_1=2T, the last expression becomes simply

$$U_{Out1} = U_{IN}\,. \tag{10}$$

That is an ideal case and the stationary state is established after first measuring cycle. The small deviation of necessary condition (R_1C_1=2T) needs a few steps instrument to reach the operational mode.

The instrument is build of next values of components: R_1=20 kΩ, C_1=2 μF R_2=3.3 kΩ, C_2=1μF, but for better presentation of stationary state achievement in simulation, for resistance R_1 10% greater value is taken (R_1=22 kΩ, instead of 20 kΩ, and R_1C_1=0,044s not exactly 0.040s).

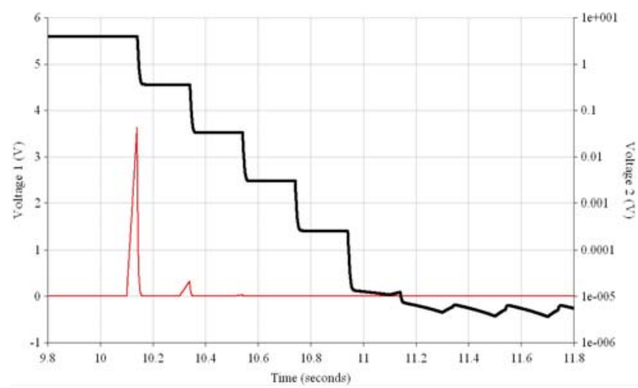

Fig.6. The ramp-up simulation diagram.

The picture above shows that the new output voltage hold circuit is able to reach stationary state in the much shorter time period (1 s). In practice, it is not quite the same; the real process is a little bit slower.

The Measuring Current Influence

The measuring current has a significant influence to the result. If the current intensity is greater, the relative error is lower, because of higher voltage on the resistor terminals [10]. But the bigger measuring current causes greater dissipation power and higher resistor temperature. It means that during the measuring process the resistance changes itself. That makes the error grater. Certainly, there must be the relationship between measuring current and relative error, which provides optimal current intensity and minimal error [8]. Hence, there is a need to find optimal conditions for a minimal systematic error as a consequence of two opposite requirements. The brief analysis and practical confirmation are explained below.

Consider relation (1) the measuring error due to limited resolution of voltage measurement ΔU_X is:

$$\Delta R_{X,(\Delta U)} = \frac{R_R}{U_R}\Delta U_X \,, \tag{11}$$

or in relative:

$$\delta_U = \frac{\Delta R_X}{R_X} = \frac{\Delta U_X}{U_X} \,. \tag{12}$$

For narrow temperature range the resistance variation depending on temperature can be expressed as:

$$R_X = R_{X0}\left(1+\alpha \cdot \vartheta\right), \tag{13}$$

where: R_{X0} - resistance at temperature ϑ_0, α - linear resistance temperature coefficient, $\Delta\vartheta$ - temperature increase.

When the low power dissipation is in question, the resistor temperature change is proportional with dissipation power and could be expressed as:

$$\Delta\vartheta = k \cdot P \,, \tag{14}$$

k - coefficient ratio (K/W).

The relationship between resistance variation and power should be shown as:

$$R_X = R_{X0}\left(1+\alpha \cdot k \cdot P\right) = R_{X0}\left(1+\delta_P\right). \tag{15}$$

δ_P - resistance error as a consequence of dissipations power (self heating).

In the worst case the total measuring error, using expressions 3 and 6, is:

$$\delta = \delta_U + \delta_P = \frac{\Delta U_X}{U_X} + \alpha \cdot k \cdot P \,. \tag{16}$$

The realized chopper stabilized low resistance comparator prototype uses the switched measuring current (on and off) [7]. With duty cycle (a) power dissipation in the resistor is:

$$P = \frac{t_I}{t_I + t_P} R_X \cdot I^2 = a \cdot R_X \cdot I^2 \,, \tag{17}$$

where: I - current pulse intensity, t_I - current switch on duration, t_P - current switch off duration,

a - duty cycle (for our comparator, a=6/10=0,6 [1, 7]).

The total measuring error could be calculated as:

$$\delta = \delta_U + \delta_P = \frac{\Delta U_X}{R_X \cdot I} + \alpha \cdot k \cdot a \cdot R_X \cdot I^2 \,. \tag{18}$$

The expression (18) gives the relation between measuring current and total error. The shape of this relation (δ) is illustrated in Figure 7.

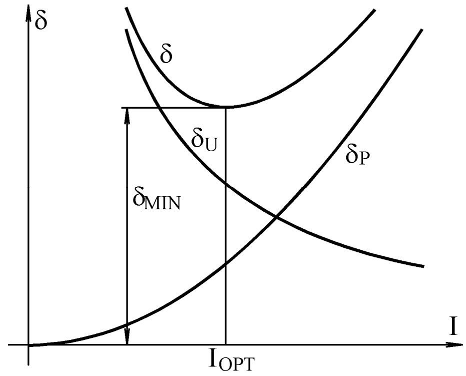

Fig.7. The measuring error curve.

Minimum value of total measuring error could be determined by solution of next equation:

$$\frac{d\delta}{dI} = -\frac{\Delta U_X}{R_X \cdot I^2} + 2 \cdot \alpha \cdot k \cdot a \cdot R_X I = 0 \,. \tag{19}$$

The solution gives the optimal measuring current as:

$$I_{OPT} = \sqrt[3]{\frac{\Delta U_X}{2 \cdot \alpha \cdot k \cdot a \cdot R_X^2}} \,. \tag{20}$$

In practical instrument realization the next values ware chosen: α=10^{-5} 1/K (worst case), k=2,5 K/W (for Thompson type of resistors [11]), a=0,6 (projected current pulse timing) and the measuring resolution of ΔU_X=10 nV. Applying those data in the above expression, for the measuring resistance range of R_{XMAX}=0,01 Ω, the optimal measuring current is:

$$I_{OPT} = \sqrt[3]{\frac{\Delta U_X}{2 \cdot \alpha \cdot k \cdot a \cdot R_X^2}} = \sqrt[3]{\frac{10^{-8}}{2 \cdot 10^{-5} \cdot 2{,}5 \cdot 0{,}6 \cdot 0.01^2}} = 1{,}49A$$

The measuring current in realized comparator is 2 A and the resolution (collective) error becomes:

$$\delta = \frac{\Delta U_X}{R_X I} + \alpha \cdot k \cdot a \cdot R_X I^2 = 1{,}1 \cdot 10^{-6} = 1{,}1\ \text{ppm}$$

The measuring error is minimal by optimal current and could be calculated by next expression:

$$\delta_{MIN} = \frac{3}{2}\sqrt[3]{\frac{2 \cdot \alpha \cdot k \cdot a \cdot \Delta U_X^2}{R_X}} \,, \tag{21}$$

and it gives common mathematical expression for the chopper stabilized low resistance comparator measuring error.

$$\delta_{MIN} = \frac{3}{2}\sqrt[3]{\frac{2 \cdot 10^{-5} \cdot 2{,}5 \cdot 0{,}6 \cdot (10^{-8})^2}{R_X}} = \frac{0{,}22 \cdot 10^{-6}}{\sqrt[3]{R_X}} \,. \tag{22}$$

The last expression is very useful for calculation of total systematic measurement error for realized chopper stabilized low resistance comparator. The value of resistance R_X defines the instrument measuring range.

Results Achieved in Practice

Considering all of the occurred problems and using the proposed solutions, realized measuring unit [1] reaches good performances [12, 13], Table1.

Table 1. The main instrument characteristics for small resistances

Measuring Range	10 mΩ	100 mΩ	1 Ω	10 Ω	100 Ω
Measuring Current	2 A	0.4 A	80 mA	16 mA	3.2 mA
Resolution (ppm)	5	1	1	1	1

Some of the instrument measuring errors is not possible to compensate. For example: the capacitor in output hold circuits self discharging, output operational amplifiers drift and offset voltages and uncertainty in the switching of the comparator [8]. But, the chosen circuits are good enough that the caused resolution is acceptable and errors are pretty small (Table 1).

The error sources like:

- parasitic voltages,
- measuring output voltage instability,
- measuring current influence ,
- long ramp-up time,

The analog switch charge injection, and similar are successfully overcome by the above discussed and proposed solutions

Conclusion

The paper presents few efficient solutions for instrument performances improvement. Many of the problems occurred by upgrading the prototype of a single range instrument for usage in different resistance ranges. Applying the explained solutions the initially goal is achieved: the unit becomes a multi-range instrument, by noncomplex modification and extension and without big costs. The stationary state establishing is significant shorted. The influence of DC and AC disturbances is decreased at acceptable level [9]. Based on described solution, the realized comparator reaches measuring resolution of 1 ppm in range of 0.01Ω to 100Ω for small resistances (Table 1).

The realized instrument (Fig. 1) is working as a prototype in a laboratory at Mining and Metallurgy Institute in Bor at this moment. There is an intention of integrating it into standard operative laboratory equipment for electrical measuring and for a new materials resistance and conductivity measurement.

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