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Resistance calibrators for verification of instruments destined for industrial applications

Abstract

Nowadays, there are some problems corresponding with specifics of industrial instrumentation metrological support, i.e., compatibility ranges of resistance reproducibility in existing calibrators and the measurement range of industrial instrumentation, disability of controlling metrological characteristics in operation mode etc. To solve such problems, the use of active resistance simulators is possible. In the paper, there is presented the proper structure of an industrial resistance calibrator together with the calibrator error analysis.

Keywords: calibration, active imitator, verification, resistance.

1. Introduction

One of the main factors determining the effectiveness of measuring instruments in industrial applications is the availability of productive metrological support. However, in recent years, along with the improvement of such instruments, there has become more noticeable the inefficiency of present methods of its metrological support. This inefficiency is due to the specifics of industrial instrumentation calibration, i.e.: firstly, the range of reproducibility of electrical signals produced by existing calibrators is not adapted to the measurement range of industrial instrumentation, which causes the use of calibrators with significant metrological redundancy; secondly, when calibrating instrumentation for industrial applications there should be determined some additional metrological parameters that are not typical for other instruments (error signalling and analogue outputs, temperature compensation circuit error caused by free ends temperature of thermocouples, measurement including connecting lines resistance together with primary transducer resistance), which requires the use of several calibrators; thirdly, because instruments for industrial applications are used mainly in industrial production lines and their dismantling is associated with significant material cost, it is important to be able to control their metrological characteristics in operation mode.

Improvement in the efficiency of metrological verification of digital instrumentation for industrial automation application has provided measurement procedures, which are greatly simplified by using industrial calibrators of high stability metrological characteristics. One of the most promising ways of creating modern industrial calibrators is based on using the structures of active resistance simulators. Therefore, the design of specialized calibrators for metrological inspection of industrial instrumentation in operating conditions is a relevant scientific and technical challenge.

2. Analysis of the structures of active resistance imitators

The only right way to solve the problems is to create code - managed measures of resistance, based on active resistance simulators [1-3]. which implemented the easiest way to modern microelectronic element base while ensuring the necessary metrological characteristics [4, 5]. The generalized structure of the simulator can be presented in the form of a serial connection of four units, namely, an input transducer (IT), a scaling converter (SC) and two buffer elements (B1, B2) (Fig. 1). IT takes effect from energy of metering object and brings it to a form convenient for further transformation; SC forms the ratio between the current flowing through the simulator and the voltage drop on it; element B1 agrees the output impedance of the input impedance of scaling converter SC, element B2 passes a signal of SC to the output of the simulator.

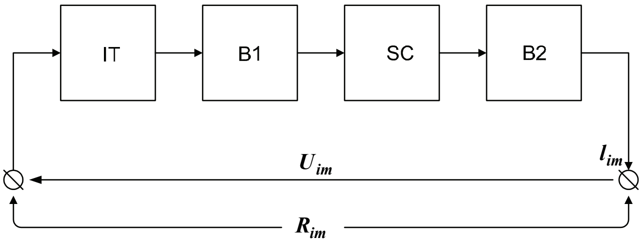

Fig. 1. Generalized structure of active resistance simulator

The nature of the structural connections between the nodes themselves and their structure determine the technical and metrological characteristics of a resistance imitator. It was investigated that imitator structure with creation of voltage on the resistance of simulator is the best decision in our task [5]. Here the measure of resistance R_N provides a transformation of a measuring current I_0 from an external source into voltage $U_n = I_0 R_N$, which after the repeater B1 (with buffer function) passes it at the input of the scaling transducer SC. The last one realises a linear transformation of input voltage with factor μ, which value depends on the code N and changes in the range from 0 to 1. A voltage at the output of scaling converter is described as follows

$$U(\mu) = \mu U_N = \mu I_o R_N . \qquad (1)$$

The source of voltage U_μ is controlled by corresponding value of output signal of a scaling converter SC. This source performs a role of the second buffer element B2. A value of imitated resistance is described as follows

$$R_{im} = \left(U_N - U_\mu\right)/I_o \ \text{ or } \ R_{im} = k_1 \mu(N) k_2 R_N , \qquad (2)$$

here k_1 and k_2 - coefficients of transformation the first B1 and the second B2 buffer element, respectively.

Values of these coefficients depend on the concrete imitator structure realization [4]. There is interesting for us the next one with transfer functions as follow

$$R_{im1} = (1 + \mu(N)) \cdot R_N ; \qquad (3)$$

Detailed analysis [5] showed that in our case the most convenient is the structure with the scaling of compensated voltage (Fig.2), which realisation is the most simplest for modern microelectronic base. This structure is based on the two operational amplifiers switched as the voltage repeater, a controlled divider of voltage and standard resistor.

3. Calibrator rational structure choice

To create effective industrial calibrator, it should offer some rational circuit solutions that will facilitate the implementation of universal functions. It needs to identify the following problems, arising from the industrial synthesis of universal calibrator:

1. To expand the range of reproducible resistance to a range of existing resistance box, it is necessary to ensure the switch range function by switching a number of standard resistors using microelectronic keys.

2. In order to better coordinate the metrological characteristics of calibrator and instruments verifying it must implement the function of inverting voltage.

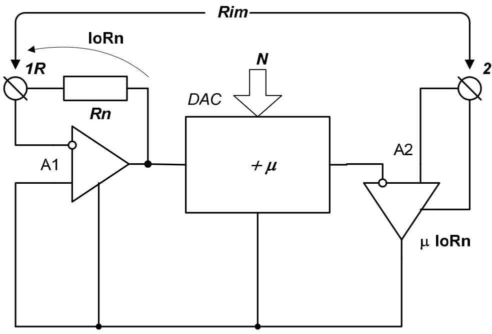

Fig. 2. Structures of an active resistance simulator with a scaling of compensated voltage

Conditions of imitator universality require the ability to reproduce a wide range of resistance. Existing scalable converters provide a dynamic range at five decimal digits at acceptable cost for mass application. To expand the range of an imitator reproduction resistances it is advisable to perform a standard resistor R_N as a multiresistor, which resistance values can be discretely set equal to the value of corresponding sub-band. The implementation of this multiresistor is possible in two ways: by parallel connection of standard resistor of value depended on the sub band of reproduction and by serial connection of standard resistors whose values are chosen from the condition of equality of the sum of the resistance values of resistors to selected sub-bands of resistance reproduction. There are possible two ways of switching value R_N, i.e.: to connect a resistor with the required value of resistance to the input terminals or to a common power bus.

When using the first option there is the problem of low resistance contact of locked key to eliminate its influence on the resistance value of the standard resistor. If try to limit a transition resistance variation of a key to a level of an additive error of calibrator resistance, then for 10 ohms range this value will be 0.0002 Ohms, which requires the use of expensive contact keys. When using the contact key a problem of termocontact electro-motive force appears that for these keys is equal to 1-2 mV/°C, which is much higher than the permissible residual voltage of resistance measures used for verifying of proper instrumentation. Compensation of these parasitic parameters is possible if provided the turning of keys in the range of operational amplifiers feedback. It is necessary to use operational amplifiers with galvanic separation from power supply, leading to an increase in prices of calibrator and thus reducing its economical effectiveness.

The best from this point of view, there is a second option where switching of multiresistor is carried out to the common power bus of the imitator. In this case, using grounding operational amplifier and turning on switching elements in his circuit of feedback, you can minimize the impact of key parasitic parameters (Fig. 3). One of the problems of synthesis of resistance calibrator is inverting voltage that occurs at the reference resistor due to the passage of measuring current. Today, the most distribution has scaling transducers based on managed dividers with an inverting of input voltage, i.e. digital to analog converters. The mass spread of such dividers and its price is quite low compared to other accomplice's code-managed dividers. It makes them appropriate for industrial use in the calibrator. To make the calibrator working in large-scale, the converter should be able to change the polarity of the input voltage.

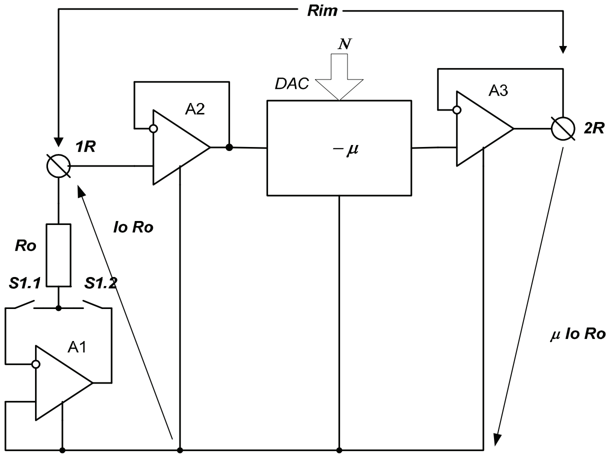

Fig. 3. Resistance imitator with standard resistors commutation to a common power bus

This can be done by switching of the input signal to the inverting input of analog-to-digital converter by a voltage inverter. The polarity change of the input voltage is depended on the sub-bands of reproduced resistance (Fig. 4). In this case, the transfer function of resistance imitator is determined by the expression as follow

$$R_{im} = (1 \pm \mu) \cdot R_N . \qquad (4)$$

If switching follower at the inverter input of digital to analog converter there is lower requirements to the parasitic parameters, because here there are relatively high signal levels.

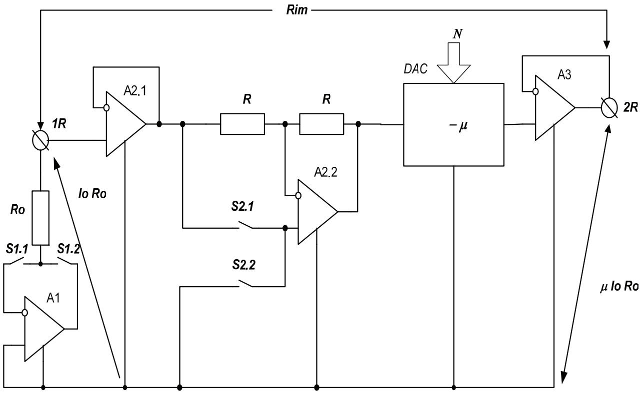

Fig. 4. Resistance imitator for resistance reproduction in the range 0 to 2R_N Ohm

For optimal coordination of reproductive resistance range of industrial calibrator with the measurement range of verifying instrumentation, it is necessary to ensure an expansion of the range of reproduction resistance from $2R_0$ to $5R_0$. The solution can be achieved by scaling of voltage taken from the standard resistor R_N, for example, such as changing the transfer ratio of the first buffer element (Fig. 5).

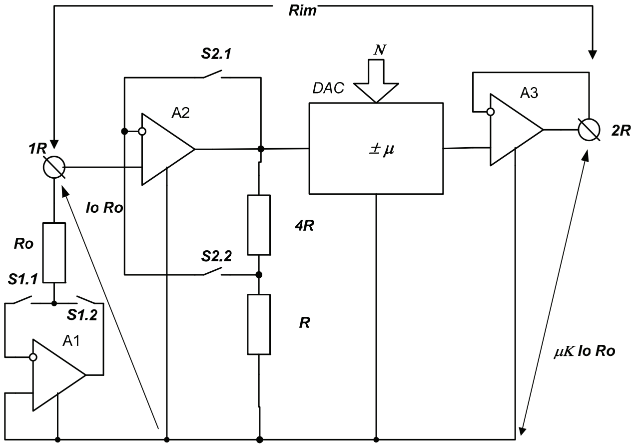

Fig. 5. Resistance imitator with a range extension by changing the gain of input operational amplifier A2

In this case we obtain the desired imitator transfer function. This way is more suitable for the construction of industry calibrators as providing the desired accuracy of transfer coefficient is much cheaper and easier than using unambiguous measures with adjustment of their resistance to nominal value. The easiest way to accomplish this purpose is to turn operational amplifier A2 in non-inverting amplifier mode with a gain of $K = 4$. To set this ratio, you can use the serial thin-film resistive matrix.

4. Active resistance simulator error analysis

Let's analyze the metrological properties of simulator resistance caused by its structural element errors. Resistance unambiguous measure of resistance is expressed as the amount of deviation ΔR_N from its nominal value R_N, i.e:

$$R_{Nr} = R_N + \Delta R_N \tag{5}$$

The error of scaling transducer, mostly is described binomial model, so its real transfer function can be written in the following form:

$$\mu_p = \mu + \Delta_{0\mu} + \delta_{S\mu} \cdot \mu \ , \tag{6}$$

where $\Delta_{0\mu}, \delta_{S\mu}\mu$ - additive and multiplicative scaling error components of the converter.

The analysis shows [5] that the additive error scaling converter consists of the input voltage quantization error and differential nonlinearity error. The coefficient of the multiplicative component of error depends on the error of fitting conversion factor and its integral nonlinearity.

Replacing a perfect model coefficients by ones that reflect their real properties (5) and (6), we obtain

$$R_{im3} = \mu \cdot R_N + \Delta_{0\mu} \cdot R_N + \left[\delta_{s\mu} \cdot R_N + \Delta R_N\right] \cdot \mu \ . \tag{7}$$

If the error imitator is normalized after the following binomial model:

$$\Delta R_{im} = \Delta_{0R} + \delta_{SR} \cdot R_{im} \ , \tag{8}$$

then using the mathematical transformations to equation (7), one can identify expressions of absolute errors of resistance reproduction as follows:

$$\Delta R_{im3} = \Delta_{0\mu} \cdot R_N + [\cdot \delta_{S\mu} + \frac{\Delta R_N}{R_N}] \cdot R_{im} \ . \tag{9}$$

From the expression (8) can be concluded that the additive component of resistance reproductive error is defined by scaling conversion errors and standard resistance value R_N, and multiplicative component of error depends on the accuracy of the model fit to the nominal value of the standard resistor and integral nonlinearity of scaling converter. It is also seen that the minimum value of the error is when reproducing minimal value of resistance, and the most meaning when reproducing close to the resistance value R_N. Analyzing the requirements for the parameters used as the circuit elements of calibrator in terms of their impact on the value of its error we have to pay attention to the following functionally independent parts, i.e.:

- Input converter, which contains multiresistor, reference voltage supply, grounded input amplifier, switching circuit;

- Scale converter that includes input buffer with a variable gain-controlled inverter, repeater, switching circuit and code-managed divider;

- Output buffer consisting of voltage transformer and switching circuit.

Thus, the use of the proposed technical solutions will create calibrating and optimizing industrial approvals for specific metrological tasks with minimal performance cost of its creation.

5. Analysis of resistance simulator frequency properties

In many practical applications an ambiguous measure of alternating current in the audio frequency range is used. Residual inductance and capacitance can trigger significant errors at higher frequencies, especially in the active multivalued resistance imitator. Even in the active resistance imitator with potentially - current compensation of closed keys active resistance ingredients the capacity of switching elements is significantly affected. When the number of bits increases then switched resistances of code - managed measure are shunted by impedance of operational amplifier galvanic separation. It is possible reduce significantly these error factors just by using active resistance imitators. The circuit impedance Z_i simulated by the imitator is determined by Ohm's law (Fig. 4)

$$Z_i = \frac{U_i}{I_i} = \frac{R_0}{k_1} + \frac{N}{1 + j\Omega_k}\left(1 - \frac{1}{k_1}\right)\left(1 - \frac{1}{k_2}\right)\left(1 - \frac{1}{k_3}\right)\left(1 - \frac{1}{k_4}\right) . \tag{10}$$

To analyse the frequency characteristics of the active resistance imitator at the first approximation, we assume that the same types of operational amplifiers are used, and

$$k_1 = k_2 = k_3 = k_4 = 1/(\mathrm{j}\Omega_1 + 1/k_0) \ , \tag{11}$$

where $\Omega_1 = \omega/\omega_1$ is a circular frequency of the operational amplifier unity gain; $\omega_1 = k_0/\tau_0$ and k_0 is a disconnected operational amplifier transmission coefficient at the zero frequency, τ_0 is open-loop operational amplifier time constant.

In light of these remarks the equation (10) can be rewritten as:

$$Z_i = R_0\left(\frac{1}{k_0} + \mathrm{j}\Omega_1\right) + N\frac{(1 + \mathrm{j}\Omega_1 - 1/k_0)^4}{1 + \mathrm{j}\Omega_k} . \tag{12}$$

Module of the amplitude vs. frequency response can be written from the expression (12) by eliminating frequency non - depended resistance value Z_{iN}, and by limiting frequency - depended components to no higher than third order of smallness. So, we have as follow:

$$Z_i = Z_{iN} - Z_{iN}\frac{\Omega_k^2}{2} + \frac{R_1^2}{Z_{iN}}\frac{\Omega_1^2}{2} + 3\frac{R_{iN}^2}{Z_{iN}}\Omega_1^2 - \frac{R_1 R_{iN}}{Z_{iN}}\left(3+\frac{\omega_1}{\omega_k}\right)\Omega_1^2\,, \tag{13}$$

where $Z_{iN} = \mu R_1\frac{R_2}{R_3}\left(1-\frac{1}{k_0}\right)^3 + \frac{R_1}{k_0}$; $R_{iN} = \mu R_1\frac{R_2}{R_3}\left(1-\frac{1}{k_0}\right)^3$.

From this equation, provided μ=0, can be defined an initial resistance value Z_{i0}, while at the value μ=1 it is obtained the maximum multiplicative error component Δ_{im} of a multivalued resistance measure, i.e.

$$Z_{i0} = \frac{R_1}{k_0}\left[1+\Omega_0^2\left(1-\frac{\omega_0^2}{2\omega_k^2}\right)\right] \text{ and } \Delta_{im} = -\frac{Z_{iN}\Omega_k^2}{2}\left(1+\frac{2\omega_k}{\omega_1}\right), \tag{14}$$

where $\Omega_0=\omega/\omega_0=\omega\tau_0$.

After the last equations there is understandable that an active resistance imitator error depends on the ratio between the frequency parameters of operational amplifier and DAC. Time constant τ_k can be determined from the passport data of DAC as follows,

$$\tau_k = \frac{1}{\omega_k} = \frac{t_{inst}}{\left|\ln\delta_{inst}\right|}\,, \tag{15}$$

where t_{inst} is the time of installing of DAC output voltage, depended on the relative error δ_{inst}.

For example, using the values of high-frequency operational amplifier type K140UD10 and multiplier DAC type KR572PA2, dynamic parameters, i.e. ω_k/ω_1=0.04; ω_0/ω_k=0.005, formulas (14) may be written as follows

$$Z_{i0} = \frac{R_1}{k_0}(1+\Omega_0^2) \text{ and } \Delta_{im} = -Z_{iN}\frac{\Omega_k^2}{2}\,. \tag{16}$$

The phase vs. frequency response of active resistance imitator is determined from the equation (13) as follows (here at the μ=1):

$$\varphi_1(\Omega) = -\mathrm{arctg}(2\Omega_1 + \Omega_k - \Omega_k^3)\,. \tag{17}$$

As we can see, an initial resistance value of active resistance imitator is determined by the parameters of the used operational amplifier, and its multiplicative error of amplitude and phase components by DAC parameters.

Simulation of electric resistance with automatic error correction by the current inversion leads to using imitators as active electrical resistance through frequency dependence of transfer factors and therefore it changes phase components of both operational amplifier and DAC. To minimize the time required to establish reproducible resistance values when changes imitator management code μ should choose an interrelation between cut frequency of low frequency filter and frequency of correction procedure adjustment. The analysis shows that a relative amplitude error of an imitator primarily depends on the bandwidth of operational amplifier used. For serial relatively inexpensive amplifier LT1115 above mentioned frequency error does not exceeds tenths of a percent at the frequency up to tens of kilohertz. So, nowadays modern microelectronic base allows producing high precision active imitators.

6. Recommendations for active resistive calibrator implementation

Comparative analysis of options for industrial calibrator based on active imitator implementing showed that the main problem lies in the choice of the element base for the criterion "accuracy - price."

In today's market there are unambiguous measure of the resistance of fitting accuracy at 0.005%, but the price is high enough (over \$100) and the need for a significant number of them have questioned the appropriateness of their use in the industrial structure of the calibrator. The authors make better use of stable serial resistors with 0.1% accuracy of the fit and function of storing realize their real values during calibration. The price of such resistors is usually located at \$1...\$10.

Calculations show that to eliminate the impact of resistance of disconnected electronic switching elements to the neglected small values it is necessary using operational amplifiers with input impedance equal or more than 30 MOhm and gain more than 10^5. Minimize the impact of operational amplifiers input currents and electronic switching element leakage currents can be achieved, provided that their value is less than 0.2 nA.

For achievement of bias voltage of an active imitator at the level nearby 5 mV it is impractical and expensive to use precision operational amplifiers. Better is use operational amplifiers which have bias voltage level (25 ... 100) mV with high performance and low cost (at \$ 10) and implemented in the structure of the calibrator support scheme periodic correction bias voltage.

As a large-scale serial converter, should be used 14...16-bit digital-to-analog resistive transducers that have high performance and stability, as well as reasonable price (\$50). Compensation nonlinearity is possible by identification during calibration procedure, on the highest range. This value is used for all ranges when resistance is reproduced.

Research conducted by the authors showed that the structural optimization of metrological characteristics of resistance calibrator, can reduce metrological characteristics requirements of industrial instrumentation the for error-scale converter in five times, and the requirements for model error resistor four times. Using serial element base combined with the use of parasitic parameter adjustment schemes calibrator (voltage bias, linearity transformation) there is possible to promote industrial calibrating instruments at the price at several hundred dollars.

7. Conclusions

Provided structural analysis shows that using operational amplifiers, integrated digital-to-analog converter and a few passive components can create meaningful measure code-managed imitators of resistance and also followed imitators of voltage and current.

Using active resistance imitator as the basic structure of the calibrator constructions for metrological inspection of industrial instrumentation can reduce the cost of calibrators and simultaneously increase their metrological reliability. An important advantage of such based calibrators is simple realization of reproduction output signals of the most transducers used in modern industrial processes.

Further studies should be carried out in the following areas: the first, to minimize connections between structural elements in the implementation of multi calibrator, secondly, to optimize the structure to reduce the requirements for elements parameters while providing the required characteristics of the calibrator.

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