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DISASSEMBLY-FREE METROLOGICAL CONTROL OF ANALOG-TO-DIGITAL CONVERTER PARAMETERS

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Abstract

The authors update the issue disassembly-free control and correction of all components of the error of measuring channels with multi-bit analog-to-digital converters (ADCs). The main disadvantages of existing methods for automatic control of the parameters of multi-bit ADCs, in particular their nonlinearity, are identified. Methods for minimizing instrumental errors and errors caused by limited internal resistances of closed switches, input and output resistances of active elements are investigated. The structures of devices for determining the multiplicative and nonlinear components of the error of multi-bit ADCs based on resistive dividers built on single-nominal resistors are proposed and analyzed. The authors propose a method for the correction of additive, multiplicative and nonlinear components of the error at each of the specified points of the conversion range during non-disassembly control of the ADC with both types of inputs. The possibility of non-disassembly control, as well as correction of multiplicative and nonlinear components of the error of multi-bit ADCs in the entire range of conversion during their on-site control is proven. ADC error correction procedures are proposed. These procedures are practically invariant to the non-informative parameters of active structures with resistive dividers composed of single-nominal resistors. In the article the prospects of practical implementation of the method of error correction during non-dismantling control of ADC parameters using the possibilities provided by modern microelectronic components are shown. The ways to minimize errors are proposed and the requirements to the choice of element parameters for the implementation of the proposed technical solutions are given. It is proved that the proposed structure can be used for non-disassembly control of multiplicative and nonlinear components of the error of precision instrumentation amplifiers.

Keywords: metrological support, analog-to-digital converter, non-disassembly control, cyber-physical system, nonlinearity, additive component of error (ACE), multiplicative component of error.

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1. Introduction

The current stage of development of information and measurement technologies is associated with the widespread use of scattered systems, primarily cyber-physical systems, and the Internet of Things. ADC is one of the most important components in the intelligent analog part of such spatially distributed multi-channel and multifunctional systems.

Thanks to the success of modern microelectronic and information technologies, accuracy, sensitivity, mass and size parameters, cost, energy consumption and other technical parameters have been improved significantly. ADCs are widely applied in a variety of technological equipment. Therefore, the technical importance of the ADC is the fact that it acts as the main bridge between the physical and digital worlds, which provides all the objective information about various controlled parameters.

Today, Industry 4.0 is booming and making extensive use of the smart grid. However, the problems of its metrological support are not fully resolved. The attention of metrologists, in particular the *European Association of National Metrology Institutes* (EURAMET) is now focused on this issue [1]. The metrological importance of ADCs is the ability to ensure the required accuracy, unity and metrological reliability in such distributed systems. Modern technologies have contributed to the development of proposals for digital support for market surveillance and verification activities, servicing of authorized bodies and manufacturers, as well as the needs of users of measuring equipment [2–5]. There are several problems of metrological support of modern electronic instruments with embedded measuring channels. We are not talking about indicators, the metrological characteristics of which are either not very strict requirements, or the consumer at his own risk decides on their operation. For other devices with standardized metrological characteristics, it is almost impossible to confirm the metrological suitability of measuring channels in the classical way due to their significant number. The process of metrological confirmation is associated with the verification of such equipment in special laboratories, accompanied by the dismantling and installation of measuring equipment at the place of operation [6, 7].

ADC is the main link between the input of information about the parameters of the "physical" world and the "digital world" in many technical devices of cyber-physical systems, Internet of Things and other multi-channel measuring systems, even household portable devices. However, the spatial scattering of such systems for the transformation of measurement information makes it very difficult to ensure the practical unity of measurements [6–8]. Due to a set of unique technical and consumer characteristics, modern ADCs are used as discrete or embedded components in a variety of areas such as Aerospace and Defense, Automotive, Communications, Energy, Healthcare, Industrial Automation Technology, Instrumentation & Measurement, Smart Buildings [7–12]. Therefore, given the massive use of ADCs it is necessary to ensure the possibility of operational metrological control of their parameters, especially at their place of operation [6–9].

2. Analytical review and problem statement

Structural and technological methods are the traditional approach to ensuring the quality of technical systems. However, they depend on the success of fundamental and materials sciences and are implemented rather slowly. In addition, the implementation of such methods is associated with a significant increase in cost, which reduces their competitiveness. However, even when using the most accurate and stable components, the performance of technical products is subject

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to temporal degradation and exposure to variable parameters of operating conditions [6–8]. Therefore, the application of structural-algorithmic (self-testing, self-diagnosis) or organizational methods (periodic metrological control) [9–12] is in this case a technical compromise.

The sole use of the methods of zero correction or of transfer coefficient is not suitable to increase accuracy due to the nonlinearity of transformation [13, 14]. There are methods for determining the parameters of the ADC such as method A which defines the static transfer characteristic in terms of the code centers, method B which defines this characteristic in terms of the code transitions, the crossplot method for measuring ADC linearity, back-to-back static ADC testing, the servo-loop code transition test, computer-based ADC servo-loop test, histogram (code density) test with both linear ramp and a sinewave input to the ADC [14–23].

However, all these methods have shortcomings that are related to the peculiarity of their technical implementation because they are primarily designed to test the ADC. Methods based on the use of precision and linear ADCs or DACs are practically not suitable for testing modern integrated multi-bit and inexpensive ADCs due to metrological and economic constraints [17, 19, 23]. The complexity of their implementation is due to the need to find the inverse function of the conversion of ADC [15, 17–19], or the application of an additional stable and/or precision AD/DAC [14, 16, 21, 23], or a static test in the form of precision DC voltage with dithering [24], or the formation of precision sinusoidal voltage [20–22]. The common disadvantage of these methods is the practical complexity of their use for non-dismantling operational metrological control of measuring channels with an ADC at the place of their operation.

To simplify the technical implementation of the time-consuming operation of devices calibration, the authors [25–27] propose to create a remote calibration system of existing equipment and a computer unit with the ability to connect to the Internet. However, the implementation of equipment and procedures for calibration of the measuring channels at the site of operation are not considered.

In terms of technical implementation, there is a very effective method based on the use of a resistive divider of single-nominal relatively inaccurate resistors. It is known that due to the processing of an array of voltage inheritance codes on the same number of groups of resistors, the conversion results will not depend on the accuracy of resistors at certain points from zero to half of the ADC conversion range [13]. To obtain another control point in the second half of the ADC conversion range, a method of switching the location of resistors is proposed. Resistors should be included in the group the same number of times during the reproduction of a certain division factor [13]. In this case, the conversion result codes will practically not depend on the instrumental errors of the resistive divider. This allows the use of such an inexpensive unit to control ADC errors throughout the temperature range of its operation. The application of such a unit makes it possible to implement the amount recommended by regulations and the distance between the controlled points of the conversion range during the control of ADC errors. Thus, for each of the monitored points evenly spaced across the conversion range, corrections can be determined and segmental-linear correction functions can be calculated for all other points of the ADC conversion range. Such a resistive unit can be the basis for the development of a system of disassembly-free metrological control or self-testing of ADCs [13].

The main disadvantage of the method of non-dismantling metrological control or self-checking of the ADC is the potentially low accuracy due to the lack of adjustment of the *additive component of error* (ACE) for each of the controlled points of the conversion range. The need to provide control at several points leads to the use of multi-channel input switches [13]. At the same time, different ways of flowing ADC input currents and reverse switching currents through the measuring circuit cause a change in the (ACE). Such an embedded resistive divider can only be used to check an ADC with a differential input. All this complicates the use of the described divider in operating conditions, especially during the implementation of a portable (removable) unit for operational metrological control of ADC parameters of measuring channels of cyber-physical systems.

3. Goal

The goal of the current article is to ensure the possibility of improving the accuracy of the method of disassembly-free metrological control or ADC self-checking. This can be achieved by adjusting the additive component of the error for each of the controlled points, which are evenly spaced across the conversion range of the ADC.

4. Correction of the additive component of error during disassembly-free control of ADC parameters

As the analysis shows, the proposed divider based on single-nominal resistors can be used as an embedded device only for testing differential ADCs with high input resistance. To test non-differential ADCs, such a divider must be supplemented by an output differential amplifier or repeater. In this case, first of all, a large value of the attenuation coefficient of the in-phase component (about 100 dB) and low nonlinearity of the transmission coefficient must be provided, because at lower values the errors from the in-phase component and the nonlinearity of the amplifier affect be commensurate with the ADC nonlinearity.

Modern element base makes it possible to provide the value of the error from the influence of the in-phase component of not more than $\pm 5 \cdot 10^{-6}$, and the error from nonlinearity of not more than $\pm 3 \cdot 10^{-6}$ using modern operational amplifiers, for example, an AD8237 [27]. Given the very low integral and differential nonlinearity (several units of LSB), relatively large values of input currents (hundreds of nA), high accuracy (gain error is approximately equal to a few thousands of a percent of *full scale* (FS)), relatively large values of bias voltages (tens of microvolts), relatively small values of input resistances (several megohms), as well as the presence of a differential input of modern integrated ADCs in the structure of the embedded disassembly-free control device, it is advisable to provide the possibility of automatic error correction [29, 30].

The device can be implemented on the basis of a divider of single-resistor resistors with the ability to include different numbers of resistors during the implementation of different separation factors (Fig. 1). Control points (0, 25, 50, 75, 100) of the conversion range can be reproduced in the divider if there are only four single-resistor resistors. This meets the requirements of the regulatory documents. With the help of output switches CT1 and CT2, voltage legacies on different combinations of resistor dividers are fed to the differential input of the ADC. The *controller* (CNT) controls the operation of the ADC and the analog *key control circuit module* (CNTM). The controller CNT also determines the adjusted ADC conversion results for each of the checkpoints.

The possibility of automatic correction of the equivalent ACE is provided by the method of sample signals. Its implementation is supposed to find the difference between two consecutive time-conversion codes, which are obtained for different input signals. One of them is the algebraic sum of the sample voltage and the equivalent ACE voltage, and the other only the equivalent ACE voltage only. The following operations are performed periodically and consecutively over time. The output of the *reference voltage source* (RVS) is connected to the input of the code-controlled resistive divider by locking key S5 and turning off key S6, and then the RVS output is turned off

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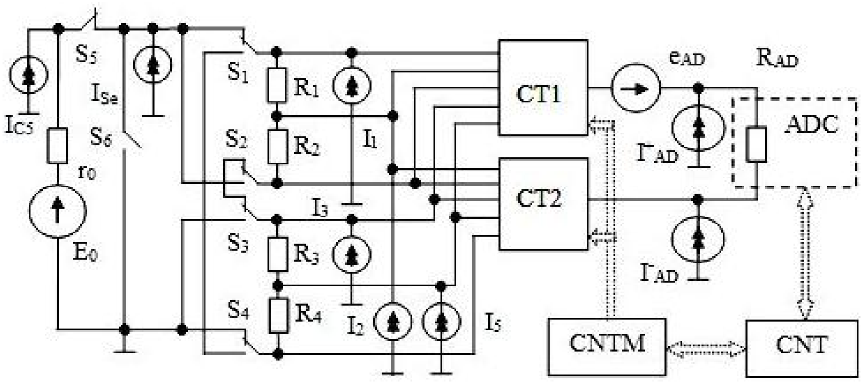

Fig. 1. Code-controlled resistive divider with automatic zero correction during ADC testing.

and the input of this divider is shortened by opening key S5 and closing key S6 [6, 7]. ACE is formed due to the ADC bias voltage and the flow through the resistors of the divider of the input currents of the ADC and reverse leakage currents and key drains.

Equivalent reverse currents of the switching elements are marked in Fig. 1: I_1, I_2, I_3 – equivalent reverse current of the first, the second and the third entrance of commutators CT1 and CT2 where:

$$I_1 = I_{1k1} + I^{+}_{AD} + I_{KM1}\,, \tag{1}$$

$$I_2 = I_{1k2} + I^{-}_{AD} + I_{2k1}\,, \tag{2}$$

$$I_3 = I_{1k3} + I_{2k2} + I_{BS2} + I_{BS3} + I_{CS21} + I_{CS31} + I_{1k4} + I_{2k3}\,, \tag{3}$$

$$I_{1k51} = I_{1k5} + I_{2k4}\,, \tag{4}$$

$$I_{Se} = I_{BS5} + I_{BS6} + I_{CS1}\,, \tag{5}$$

I_{C5}, I_{Se} – equivalent reverse current of keys; I_{BS5}, I_{BS6} – reverse currents of source-body transitions for keys S_5 and S_6; I_{CS1}, I_{C5} – reverse currents of drain-body transitions for keys S_5 and S_{11}.

Since the error value can be set with an error of tenths of a percent, the assumption is made that the value of the reverse currents does not depend on the value of the switched signals, the resistance values of the closed keys are much smaller than the resistances of the scaling resistors. Therefore, in this analysis, an assumption is made that the adjacent connected pins of resistors R_2 and R_3 are equipotential and, in the first approximation, the components of the second order of smallness are neglected during the ACE determination.

The value of equivalent ACE will depend on the implementation of a certain control point, but so that the ADC measures the legacy of voltage on the same number of different resistors of the divider. The mathematical model of switching of each of the divider four resistors is investigated. When measuring the ADC inheritance voltage U_1 on resistor R_1, the equivalent input voltage U_1^{+} of the non-inverting ADC input is defined similarly to [13]:

$$U_1^{+} = E_0 \frac{4\overline{R} + r_{S21} + r_{S31}}{R_C} + E_0 k_{pc1} + \Delta_{11a}\,, \tag{6}$$

with

$$\Delta_{11a} = I^{+}_{ADe} r_{1k1} - I_{1k21} R_{1e} - I_{1k31} R_{2e} - I_{1k51} R_{3e} + e_{AD}\,, \tag{7}$$

$$\overline{R} = \frac{1}{4}\sum_{i=1}^{4} R_{\mathrm{i}}\,, \tag{8}$$

$$R_{\mathrm{i}} = \overline{R}\,(1+\delta_{\mathrm{i}})\,, \tag{9}$$

$$I^{+}_{\mathrm{ADe}} = I^{+}_{\mathrm{AD}} + I_{\mathrm{KM1}}\,, \tag{10}$$

$$I_{1\mathrm{k}21} = I^{-}_{\mathrm{ADe}} + I_{1\mathrm{k}2} + I_{2\mathrm{k}1}\,, \tag{11}$$

$$I^{-}_{\mathrm{ADe}} = I^{-}_{\mathrm{AD}} + I_{\mathrm{KM2}}\,, \tag{12}$$

$$I_{1\mathrm{k}31} = I_{1\mathrm{k}3} + I_{2\mathrm{k}2} + I_{\mathrm{BS2}} + I_{\mathrm{BS3}} + I_{\mathrm{CS21}} + I_{\mathrm{CS31}} + I_{1\mathrm{k}4} + I_{2\mathrm{k}3}\,, \tag{13}$$

$$I_{1\mathrm{k}51} = I_{1\mathrm{k}5} + I_{2\mathrm{k}4};\quad I_{1\mathrm{k}5}\,, \tag{14}$$

$$R_{\mathrm{C}} = 4\overline{R} + r_{\mathrm{SC}}\,, \tag{15}$$

$$\frac{1}{4}\sum_{\mathrm{i}=1}^{4} R_{\mathrm{i}} = 4\overline{R}, \tag{16}$$

$$r_{\mathrm{SC}} = r_{\mathrm{S11}} + r_{\mathrm{S21}} + r_{\mathrm{S31}} + r_{\mathrm{S41}} + r_{\mathrm{S5}} + r_0\,, \tag{17}$$

$$R_{1\mathrm{e}} = \frac{R_1\left(4\overline{R} + r_{\mathrm{S21}} + r_{\mathrm{S31}} - R_1\right)}{4\overline{R} + r_{\mathrm{S21}} + r_{\mathrm{S31}}}\,, \tag{18}$$

$$R_{2\mathrm{e}} = \frac{\left(4\overline{R} + r_{\mathrm{S21}} + r_{\mathrm{S31}} - R_1 - R_2\right)}{4\overline{R} + r_{\mathrm{S21}} + r_{\mathrm{S31}}}R_1\,, \tag{19}$$

$$R_{3\mathrm{e}} = \frac{R_4}{4\overline{R} + r_{\mathrm{S21}} + r_{\mathrm{S31}}}R_1\,, \tag{20}$$

where: E_0 – source voltage of reference voltage; e_{AD} – bias voltage at the ADC input; $\overline{R}$ – the average value of the resistance of the divider resistors; R_{i} – the resistance of the i-th divider resistor; I^{+}_{AD} – leakage current of non-inverting ADC input; I_{KM1} – reverse leakage current of the CT1 switch; I^{-}_{AD} – leakage current of the inverting input of the ADC; I_{KM2} – reverse leakage current of the CT2 switch; $I_{1\mathrm{k}2}$, $I_{2\mathrm{k}1}$ – reverse drain currents, respectively, the second input of the switch CT1 and the first input of the switch CT2; $I_{1\mathrm{k}3}$, $I_{2\mathrm{k}2}$ – reverse drain currents, respectively, the third input of the switch CT1 and the second input of the switch CT2; I_{BS2}, I_{BS3}, I_{CS21}, I_{CS31} – reverse currents, respectively, the source of the second S_2 and the third S_3 switches and switch drains S_{21} and S_{31}; $I_{1\mathrm{k}4}$, $I_{2\mathrm{k}3}$ – reverse drain currents, respectively, the fourth input of the switch CT1 and the third input of the switch CT1; $I_{1\mathrm{k}5}$, $I_{2\mathrm{k}4}$ – reverse drain currents, respectively, the fifth input of the switch CT1 and the fourth input of the switch CT2; r_{S11}, r_{S21}, r_{S31}, r_{S41}, r_{S5} – resistances of the locked key, respectively S_{11}, S_{21}, S_{31}, S_{41}, S_5; r_0 – internal resistance of RVS; $r_{1\mathrm{k}1}$, $r_{1\mathrm{k}2}$, $r_{1\mathrm{k}3}$, $r_{1\mathrm{k}4}$ – the support of the closed keys of the corresponding inputs of the switch CT1; $r_{2\mathrm{k}1}$, $r_{2\mathrm{k}2}$, $r_{2\mathrm{k}3}$, $r_{2\mathrm{k}4}$ – the support of the closed keys of the corresponding inputs of the switch CT2; $R_{1\mathrm{e}}$, $R_{2\mathrm{e}}$, R_{3e} – equivalent resistance for reverse current flow relative to the second, third and fourth inputs of the switch CT1, respectively; k_{pc1} – the attenuation coefficient of the in-phase component of the non-inverting ADC input. Given that the resistances of large-scale resistors in practice are much larger than the resistances of the closed keys and $R_{\mathrm{i}} \cong \overline{R}$, their support during the determination of ACE can be neglected.

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For the same reason, the outputs of the lower resistors in Fig. 1, i.e. resistor R_2 and upper resistor R_3, can be considered equipotential. Then the equivalent supports can be roughly given as:

$$R_{1e} \cong \frac{3}{4}\overline{R}, \tag{21}$$

$$R_{2e} \cong \frac{1}{2}\overline{R}, \tag{22}$$

$$R_{3e} \cong \frac{1}{4}\overline{R}. \tag{23}$$

The equivalent input voltage U_1^- of the inverting ADC input is given similarly to [13]:

$$U_1^- \cong E_0 \frac{4\overline{R} - R_1 + r_{S21} + r_{S31}}{R_C} + \frac{3}{4} E_0 k_{pc2} + I_{ADe}^- r_{2k1}\,, \tag{24}$$

with

$$I_{ADe}^- = I_{AD}^- + I_{KM2}\,, \tag{25}$$

where: I_{AD}^- – leakage current of the inverting input of the ADC; I_{KM2} – reverse leakage current of the CT2 switch; r_{2k1} – resistance of the closed first key of the CT2 switch; k_{pc2} – the attenuation coefficient of the in-phase component of the inverting ADC input.

The value of the ADC input voltage when measuring the voltage drop $U_1 = U_1^+ - U_1^-$ on resistance R_1 is defined as the difference of expressions (6) and (24):

$$U_1 \cong E_0 \frac{R_1}{R_C} + e_{AD} + \Delta_{pc1} + \Delta_{a1}\,, \tag{26}$$

where:

$$\Delta_{a1} = \left(I_{ADe}^+ r_{1k1} - I_{ADe}^- r_{2k1}\right) - \frac{3}{4} I_{1k21}\overline{R} - \frac{\overline{R}}{2}\left(I_{1k31} + I_{1k41}\right) - \frac{\overline{R}}{4} I_{1k51};$$

$$\Delta_{pc1} = E_0 \left(k_{c\phi 1} - \frac{3}{4} k_{pc2}\right).$$

By analogy, when measured voltage drops:

$$U_2 = U_2^+ - U_2^-, \tag{27}$$

$$U_3 = U_3^+ - U_3^-, \tag{28}$$

$$U_4 = U_4^+ - U_4^- \tag{29}$$

on resistances R_2, R_3, R_4 similar ratios are obtained:

$$U_2 \cong E_0 \frac{R_2}{R_C} + e_{AD} + \Delta_{pc2} + \Delta_{a2}\,, \tag{30}$$

$$U_3 \cong E_0 \frac{R_3}{R_C} + e_{AD} + \Delta_{pc3} + \Delta_{a3}\,, \tag{31}$$

$$U_4 \cong E_0 \frac{R_4}{R_C} + e_{AD} + \Delta_{pc4} + \Delta_{a4}\,, \tag{32}$$

where:

$$\Delta_{pc4} = E_0 \frac{3}{4} k_{pc1};$$

$$\Delta_{a2} = \left(I^{+}_{\text{ADe}} r_{1k2} - I^{-}_{\text{ADe}} r_{2k2}\right) + \frac{3}{4}\left(I^{+}_{\text{ADe}} + I_{1k2} + I_{2k1}\right)\overline{R} - \frac{\overline{R}}{2}\left(I_{1k31} + I^{-}_{\text{ADe}}\right) - \frac{\overline{R}}{4} I_{1k51};$$
$$\Delta_{a3} = \left(I^{+}_{\text{ADe}} r_{1k4} - I^{-}_{\text{ADe}} r_{2k4}\right) + \frac{3}{4}\left(I_{1k2} + I_{2k1}\right)\overline{R} - \frac{\overline{R}}{2}\left(I_{1k31} + I^{-}_{\text{ADe}}\right) - \frac{\overline{R}}{4} I_{1k51};$$
$$\Delta_{pc2} = E_0\left(\frac{3}{4}k_{pc1} - \frac{1}{2}k_{pc2}\right);$$
$$\Delta_{a4} = \left(I^{+}_{\text{ADe}} r_{1k4} - I^{-}_{\text{ADe}} r_{2k4}\right) + \frac{3}{4}\left(I_{1k2} + I_{2k1}\right)\overline{R} - \frac{\overline{R}}{2}\left(I_{1k31} + I^{-}_{\text{ADe}}\right) - \frac{\overline{R}}{4} I_{1k51};$$
$$\Delta_{pc3} = E_0\left(\frac{3}{4}k_{pc1} - \frac{1}{2}k_{pc2}\right).$$

Analysis of relations (30)–(32) shows that the value of the equivalent ACE will depend on the position of the resistor which measures the voltage drop using the ADC. In addition, switching the positions of the scale resistors during the implementation of the nominal value of the division factor of 0.75 will lead to additional changes in the value of the ACE. An obvious and traditional solution is to use a high-quality element base – switches with low resistance values in the closed state and low reverse currents.

Even in this case, the value of the ACE will remain quite large, caused by the bias voltage of the ADC and its input currents, the values of which even for modern chips can be, respectively, tens of microvolts and hundreds of nanoamperes [29, 30]. In addition, embedded systems for metrological control of ADC parameters should have increased metrological reliability. In many cases, the described method can be implemented on the basis of programmable systems on a chip, which includes the basic elements for its practical implementation [31].

However, the parameters of the element base of such systems are significantly worse than the parameters of the best switching elements [32]. Due to potentially high metrological properties of the analyzed method it can be implemented on a conventional element base, the parameters of which are also not the best. Given the fact that in practice the metrological control of ADC parameters is carried out at fairly long intervals, it is proposed to automatically adjust the ACE after each change of switching voltage, which should be carried out by the method of sample signals [6, 7].

In this case, the values of equivalent ACEs will not change. Indeed, if the RVS is disconnected and the splitter input is connected to a common bus, the equivalent ACEs for the above configurations can be represented by the following relations:

$$\Delta U_1 = e_{\text{AD}} + \left(I^{+}_{\text{ADe}} r_{1k1} - I^{-}_{\text{ADe}} r_{2k1}\right) - \frac{3}{4} I_{1k21}\overline{R} - \frac{\overline{R}}{2}\left(I_{1k31} + I_{1k41}\right) - \frac{\overline{R}}{4} I_{1k51}\,, \tag{33}$$

$$\Delta U_2 = e_{\text{AD}} + \left(I^{+}_{\text{ADe}} r_{1k2} - I^{-}_{\text{ADe}} r_{2k2}\right) + \frac{3}{4}\left(I^{+}_{\text{ADe}} + I_{1k2} + I_{2k1}\right)\overline{R} - \left(I_{1k31} + I^{-}_{\text{ADe}}\right)\frac{\overline{R}}{2} - I_{1k51}\frac{\overline{R}}{4}\,, \tag{34}$$

$$\Delta U_3 = e_{\text{AD}} + \left(I^{+}_{\text{ADe}} r_{1k4} - I^{-}_{\text{ADe}} r_{2k4}\right) + \frac{3}{4}\left(I_{1k2} + I_{2k1}\right)\overline{R} - \left(I_{1k31} + I^{-}_{\text{ADe}}\right)\frac{\overline{R}}{2} - I_{1k51}\frac{\overline{R}}{4}\,, \tag{35}$$

$$\Delta U_4 = e_{\text{AD}} + \left(I^{+}_{\text{ADe}} r_{1k4} - I^{-}_{\text{ADe}} r_{2k5}\right) + \frac{3}{4}\left(I_{1k2} + I_{2k1}\right)\overline{R} - \left(I_{1k31} + I^{+}_{\text{ADe}}\right)\frac{\overline{R}}{2} - I_{1k51}\frac{\overline{R}}{4}\,. \tag{36}$$

The adjusted values of the controlled point codes will be stored in the CNT controller of the measuring system similarly to [13]:

$$N_{1k} = k_{\text{AD}}\left(E_0 \frac{R_1}{4\overline{R} + r_{\text{SC}}} + \Delta_{pc1}\right), \tag{37}$$

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$$N_{2k} = k_{AD}\left(E_0 \frac{R_2}{4\overline{R} + r_{SC}} + \Delta_{pc2}\right), \tag{38}$$

$$N_{3k} = k_{AD}\left(E_0 \frac{R_3}{4\overline{R} + r_{SC}} + \Delta_{pc3}\right), \tag{39}$$

$$N_{4k} = k_{AD}\left(E_0 \frac{R_4}{4\overline{R} + r_{SC}} + \Delta_{pc4}\right). \tag{40}$$

In the case of application of the classic structure of the resistive divider without an automatic adjustment ACE, the analysis of expressions (37)–(40) shows that the errors from the bias voltages and ADC input currents will also be corrected manually during the experimental determination of errors. However, the necessity to establish the value of such corrections for each of the division factors (several ADC checkpoints) and the dependence of ACE values on environmental and time conditions makes such an operation impractical.

Obviously, in differential ADCs, the value of the error due to the limited attenuation coefficient of the in-phase component should be several times smaller than the error of their integral nonlinearity. However, even then, the error in determining the integral nonlinearity of the ADC will be affected by the error due to the influence of the resistance of the closed keys. To reduce it, additional measurement of voltage legacy on the supports of closed switches $r_{S21} + r_{S31}$ is proposed [13]. The determined value of the code N_{025} of a certain checkpoint will be found as the arithmetic mean of the codes for expressions (37)–(40) and taking into account the obvious relationship [13] as:

$$N_{025} = \frac{1}{4}\sum_{i=1}^{4} N_{ik} = \frac{1}{4}\sum_{i=1}^{4}\left[k_{AD}E_0\left(\frac{R_i}{4\overline{R} + r_{SC}}\right)\right] = \frac{1}{4}\sum_{i=1}^{4}\left[k_{AD}E_0\left(\frac{4\overline{R}}{4\overline{R} + r_{SC}}\right)\right]. \tag{41}$$

After decomposing the denominator of expression (41) into a series under the conditions $4\overline{R} \gg r_{SC}$ and the restriction of the members of the first order of smallness is obtained expression similarly to [13]:

$$N_{025} = \sum_{i=1}^{4}\left[k_{AD}\frac{E_0}{4}\left(1 - \frac{r_{SC}}{4\overline{R}}\right)\right]. \tag{42}$$

The analysis shows that the error of the influence of the resistance of the locked keys can be reduced to values caused only by the scatter of their values. To do this, a double value of the code must be added to the right part of expression (42). It is proportional to the voltage drops on the supports of the closed keys $r_{S21} + r_{S31}$. If the resistance of the closed keys is given through the average value of r_S on resistance and on resistance match between channels Δr_{Si}, the result code will be defined as:

$$\begin{aligned} N_{025S} &= \sum_{i=1}^{4}\left\{k_{AD}\frac{E_0}{4}\left[1 - \frac{r_{SC} - 2\left(r_{S21} + r_{S31}\right)}{4\overline{R}}\right]\right\} \\ &= \sum_{i=1}^{4}\left\{k_{AD}\frac{E_0}{4}\left[1 - \frac{r_{S5} + r_0 + \left(\Delta r_{S11} + \Delta r_{S41}\right) - \left(\Delta r_{S21} + \Delta r_{S31}\right)}{4\overline{R}}\right]\right\}. \end{aligned} \tag{43}$$

The spread of measurement result codes will be determined only by possible changes in the resistance of the switching elements. When using a chip with high-quality switches, such as the ADG888, the equivalent spread of closed switches will not exceed only 0.28 ohms. In fact, for an ADG888 microcircuit, the on resistance of its keys does not exceed 0.55 ohm, and the on resistance match between channels does not exceed 0.07 ohm [32].

After adjusting error Δ_{025}, ADC at this controlled point can be determined as:

$$\Delta N_{025} = N_{025S} - 0.25 N_{clb}\,, \tag{44}$$

$$N_{clb} = k_{AD} E_{clb}\,, \tag{45}$$

where: N_{clb} – code obtained during ADC calibration.

Similarly, ratios for other controlled points of 0.5 and 0.75 of the ADC conversion range can be obtained.

5. Prospects for the practical implementation of the method of correcting errors in the control of ADC parameters

Methodological errors from the influence of the resistance of the closed keys r_{S5} and the internal resistance r_0 RVS can be reduced in the traditional way. For example, when selecting appropriate scale values for scale resistors, provided that the values are less than the integral nonlinearity of multi-bit ADCs (0.001 . . . 0.003)%, the values of the scale resistors should be greater than several megohms (> 2 Mohm).

The methodological error will increase significantly due to the limited input resistance of the ADC. For ADCs with low input resistance (of the order of several megohms), this method becomes impractical [32]. Therefore, to ensure the ability to control the parameters of any ADC buffer repeaters should be used at the outputs of the device, as well as at the output of the reference voltage source (Fig. 2).

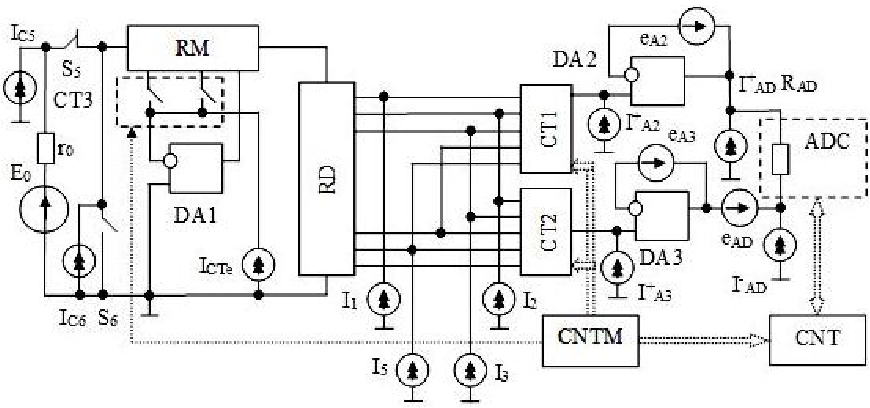

Fig. 2. Improved device for operative metrological monitoring of measuring channels of cyber-physical systems.

In Fig. 2 there are I_1, I_2, I_3, I_5 – the equivalent reverse currents of switching elements, which are the same as in Fig. 1.

$$I_{STe} = I^+_{A1} + I_{CST3} + I_{BSTi}\,, \tag{46}$$

where: I_{STe} – the equivalent reverse current of switch keys CT3; I^+_{A1} – the reverse current of the non-inverting input of the amplifier DA1; I_{CST3} – the summary reverse current of source-body transitions of all keys of switch CT3; I_{BSTi} – the reverse current of drain-body transitions of the

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turned on switch key CT3; I^{+}_{A2}, I^{+}_{A3} – the reverse currents of of non-inverting inputs, respectively, of the amplifiers DA2 and DA3; e_{A2}, e_{A3} – bias voltages, respectively, of the amplifiers DA2 and DA3.

In this structure repeaters DA2 and DA3 are used to significantly reduce the methodological errors caused by limited input resistance of the ADC voltage. Since the output resistance of voltage repeaters based on modern operational amplifiers is very small (less than ten thousandths of an ohm), the analyzed methodological error can be neglected for almost all applications of the proposed device. Errors caused by the finiteness of the common-mode attenuation component of classical non-inverting voltage repeaters can be significantly reduced by choosing high-quality and inexpensive instrumental operational amplifiers, for example, type AD8237 [28]. With their use, the error from the influence of the in-phase component can be reduced to values not exceeding 0.001%. In practice, the effect of this component of the error can be eliminated with the application of voltage repeaters DA2 and DA3 with galvanically separated power supplies [7]. To this end, the industry manufactures special chips, such as types ADuM5020, ADuM5028 [34].

Modern ADC chips and measuring amplifiers are usually made in many ranges [28–30, 33]. Therefore, in the proposed device, the scaling unit based on the operational amplifier DA1 is provided (Fig. 2). The transmission factor is set by a *resistive matrix* (RM) formed from series-connected resistors, the potential outputs of which are used to automatically switch it by the switch CT3 [32, 35]. The high input resistance of this stage makes it possible to significantly reduce the methodological errors from the influence of the resistance of the closed key S5 and internal resistance r_0. This allows to reduce the methodical errors caused by the closed keys rSi resistance. In fact, due to choosing sufficiently large values scaling resistances, this error will not exceed the settled values for different conversion coefficients of the resistive divider RD.

For example, for the values of the resistance of the closed keys above to ensure a methodological error of not more than 0.001%, the values of the scaling resistors must be selected to be not less than 200 kohm. In the case of determining and calculating the correction for the average value of resistance, the specified values of resistance must already be not less than 30 kohm. Such values of the resistance of the scaling resistors are acceptable for practical use. Equivalent ACE of repeaters DA2, DA3 and scaling converter DA1 will be adjusted similarly to the method of sample signals described above. The RVS is disconnected from the input of the operational control device and the input is connected to the common bus after each change of configuration or transfer coefficients of individual units.

6. Discussion of the results

All devices described in the literature are intended for direct or indirect determination of ADC nonlinearity and therefore they require experimental study at almost every point in the ADC conversion range. This article aims to provide the ability to calibrate the measurement channels of the ADC at several points in its conversion range as required by regulations. Therefore, the authors proposed a method, algorithm and device for the implementation of non-disassembly calibration of measuring channels in operating conditions. This makes it possible to implement a simple, cheap and small device for calibration of measuring channels in situ.

The main purpose of this study is to develop theoretical prerequisites and substantiate the practical feasibility of portable device application for calibration of any digital measuring channels without dismantling them from the place of operation. The authors showed that the uncorrected error value may not exceed a few least significant bits. Automatic adjustment of ACE by the method of sample signals is well tested experimentally and confirmed by the practice of its implementation in serial digital devices A565, CR7701 [6–8].

In particular, the unadjusted ACE value in these digital devices is a few tenths of a microvolt. Today, digital measuring channels are widely used as individual devices, and especially built into other electronic devices, such as multichannel measuring instruments, Internet of Things, controllers, regulators and more. In such systems, traceability, calibration or uniformity of measurements is always very difficult to ensure, which does not guarantee the quality of products, goods and services manufactured with them.

In many cases, the problem of metrological confirmation of measuring channels of mass use is technically and organizationally unsolved and its solution is practically left to the owner. In this paper, an attempt to develop theoretical and practical foundations for the creation of small and precision devices for metrological confirmation of digital measuring channels at the in situ is made.

During the practical implementation of the proposed device, its metrological characteristics can be confirmed in special measuring or calibration laboratories. If necessary, the corrections are saved in the device controller. Practical insensitivity to the influence of changing environmental conditions can be ensured due to the help of constructive-technological methods. The developed structure can be implemented as small and inexpensive, for example, on the basis of programmable systems on a chip [31].

Such a designed and manufactured low-size device can be brought to place of operation, connected to the measuring channels and used for their calibration in situ.

As shown above, the theoretical analysis of the use of the proposed method and device makes it possible to explicitly determine and, consequently, correct the error from the nonlinearity of the ADC of almost any bit at several fixed points in the conversion range. In this case, the additive component of the error of both the control device and the ADC will be corrected simultaneously. The uncorrected value of errors will not exceed half the equivalent unit of the lower digit of the measurement result, which will practically increase in $\sqrt{m}$ times, where: m is the number of performed mathematical operations.

It is known that the uncorrected value of error caused by noise in devices with automatic correction (junction unit) depends on the noise characteristics of operational amplifiers. Thus, the practice of industrial operation of serial digital devices of types A565, CR7701 has shown that even when using the cheapest element base, the value of the standard deviation of the random noise error will be equal to tenths of a microvolt [7, 9]. The analysis shows that for modern operational amplifiers and ADCs the unadjusted value of the additive component of the error will not exceed the specified value.

To estimate the threshold capabilities of the proposed method of adjustment, the ADC conversion function can practically be approximated only by the largest quadratic component. The analysis shows that the limit of the allowable values of nonlinearity error will depend on the width of the transformation range. When using the proposed method, the value of the ADC nonlinearity error is clearly determined at several points in the subband of the conversion similarly to, for example, relation (44). That is, the whole range of conversion for nonlinearity correction will be divided into subbands, the number of which will be determined by the number of resistors used. For the quadratic component, the threshold value of the error from nonlinearity will decrease inversely the quadratic dependence on the value of the multiplicity of narrowing the range of transformation. If the divider of only two resistors is used, the value of the nonlinearity error can be reduced four times, and the value of the four resistors can be reduced sixteen times. It should be noted that with a further increase in the number of resistors of the divider, for example, up to ten, the decrease in the value of the error of nonlinearity slows down, but will be two

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orders of magnitude. However, in this case, the complexity of technical implementation will also increase significantly due to the growing number of switching elements and the need to process a significant array of transformation results.

The relative simplicity of the proposed device for determining the error from the nonlinearity of the ADC with simultaneous adjustment of the additive component of the error allows to apply it as a built-in or removable unit to provide operational quality control of measuring channels in intelligent measuring systems.

7. Conclusions

The analysis showed that for the practical implementation of non-dismantling metrological control of ADC parameters, in addition to nonlinear, the equivalent additive component of the error of the entire measuring path should be adjusted as well. This can be achieved by the method of sample signals for each of the division factors of the resistive divider, composed of series-connected single-nominal resistors. Adjusted code values are obtained as the difference between the values of the current ADC codes obtained with the reference voltage connected and disconnected from the divider.

After adjusting the additive component for each of the controlled points of the conversion range, the integrated nonlinearity of the ADC is defined as the difference between the current value of the code and the nominal value of the code for the specified resistivity of the resistive divider.

To reduce the methodological errors caused by the limited input resistance of the ADC, before its inputs, it is advisable to use buffer repeaters. Additive offsets of such repeaters will be adjusted by the proposed method. In order to reduce methodological errors due to the limited values of the common mode rejection coefficient of repeaters, in addition to the traditional choice of high-quality operational amplifiers, the feasibility of using amplifiers with galvanically separated power supplies has been proven.

It is proposed to use a large-scale active divider with potential recomputation of its separation coefficients for metrological control of parameters of multiband ADCs. The partition coefficients are set by a resistive circuit.

Possibilities of realization of the offered technical decisions on the basis of both discrete and integral components (for example, programmable systems on a chip) are analyzed. It has been shown that due to the possibility of automatic adjustment of the additive component, the metrological parameters of the proposed structure will be practically determined only by the multiplicative components of errors.

References

[1] Piquenmal, F., Jeckelmann, B., Callegaro, L., Hallstrom, J., Janssen, T. J. B. M., Melcher, J., Rietveld, G., Siegner, U., Wright, P., & Zeier, M. (2017). Metrology in electricity and magnetism: EURAMET activities today and tomorrow. *Metrologia*, *54*(5). R1-R24. https://doi.org/10.1088/1681-7575/aa7cae

[2] Thiel, F. (2018). Digital transformation of legal metrology—The European metrology cloud. *OIML Bull*, *59*(1), 10-21. https://www.oiml.org/en/publications/bulletin/pdf/oiml_bulletin_jan_2018.pdf

[3] Thiel, F., Esche, M., Toro, F. G., Oppermann, A., Wetzlich, J., & Peters, D. (2017). The European metrology cloud. *In 18th International Congress of Metrology (p. 09001)*. EDP Sciences. https://doi.org/10.1051/metrology/201709001

[4] Nordholz, J., Dohlus, M., Graflich, J., Kammeyer, A., Nischwitz, M., Wetzlich, J., Yurchenko, A., & Thiel, F. (2021). Evolution of the European Metrology Cloud. *OIML Bulletin*, *62*(3), 25–34. https://www.oiml.org/en/publications/bulletin/pdf/oiml_bulletin_july_2021.pdf

[5] Toro, F. G., & Lehmann, H. (2021). Brief overview of the future of metrology. *Measurement: Sensors*, 18, 100306. https://doi.org/10.1016/j.measen.2021.100306

[6] Stadnyk, B., Mykyychuk, M., Yatsyshyn, S., Fröhlich, T., Mastylo, R., & Yatsuk, V. (2021). Open-science space issue: calibration of measuring channels non-dismantling cyber-physical systems. *Measuring Equipment and Metrology*, *82*(3), 12-17. https://doi.org/10.23939/istcmtm2021.03.012

[7] Yatsyshyn S., & Stadnyk B. (2017). *Cyber-Physical Systems: Metrological Issues* (1st ed.). IFSA Publishing.

[8] Yatsyshyn S., & Stadnyk B. (2021), *Cyber-Physical Systems and Metrology 4.0* (1^{st} ed.). IFSA Publishing.

[9] Yatsuk, V., Mykyjchuk, M., & Bubela, T. (2020). Ensuring the measurement efficiency in dispersed measuring systems for energy objects. *In Sustainable Production: Novel Trends in Energy, Environment and Material Systems* (pp. 131–149). Springer, Cham. https://doi.org/10.1007/978-3-030-11274-5_9

[10] Jun, S., Kochan, O., Chunzhi, W., & Kochan, R. (2015). Theoretical and experimental research of error of method of thermocouple with controlled profile of temperature field. *Measurement Science Review*, *15*(6), 304. https://doi.org/10.1515/msr-2015-0041

[11] Jun, S., Kochan, O., & Kochan, R. (2016). Thermocouples with built-in self-testing. *International Journal of Thermophysics*, *37*(4), 1-9. https://doi.org/10.1007/s10765-016-2044-2

[12] Stadnyk, B., Yatsyshyn, S., & Seheda, O. (2012). Research in Nanothermometry. Part 6. Metrology of Raman Thermometer with universal calibration artifacts, *Sensors & Transducers*, *142*(7), 1–9. https://www.sensorsportal.com/HTML/DIGEST/P_1002.htm

[13] Kochan, R. (2012). *Precyzijni analogo-cyfrovi peretvoruvachi z bezdemontazhnoyu perevirkoyu*. Lviv Polytechnica Publishing House (in Ukrainian)

[14] Kester, W. (2005). *The Data Conversion Handbook*. Elsevier. https://www.analog.com/en/education/education-library/data-conversion-handbook.html

[15] Haasz, V. (2003, September). Testing of high-resolution/middle-speed A/D converters and modules problems and ways of their solving. *In Second IEEE International Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, 2003. Proceedings* (pp. 7–12). IEEE. https://doi.org/10.1109/IDAACS.2003.1249505

[16] Eduri, U., & Maloberti, F. (2001, September). On-line digital correction of the harmonic distortion in analog-to-digital converters. *In ICECS 2001. 8th IEEE International Conference on Electronics, Circuits and Systems (Cat. No. 01EX483)* (Vol. 2, pp. 837–840). IEEE. https://doi.org/10.1109/ICECS.2001.957604

[17] Björsell, N., & Händel, P. (2007). Achievable ADC performance by postcorrection utilizing dynamic modeling of the integral nonlinearity. *EURASIP Journal on Advances in Signal Processing, 2008*, 1–10. https://doi.org/10.1155/2008/497187

[18] Suchanek, P., Slepicka, D., & Haasz, V. (2008). Several approaches to ADC transfer function approximation and their application for ADC non-linearity correction. *Metrology and Measurement Systems*, *15*(4), 501–511.

Metrol. Meas. Syst., Vol. 29 (2022), No. 4, pp. 669–684
DOI: 10.24425/mms.2022.143068

[19] Suchanek, P., Haasz, V., & Slepicka, D. (2009, September). ADC nonlinearity correction based on INL(n) approximations. *In 2009 IEEE International Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications* (pp. 137–140). IEEE. https://doi.org/10.1109/IDAACS.2009.5343008

[20] Carnì, D. L., & Grimaldi, D. (2007, September). State of Art on the Tests for ΣΔ ADC. In *15th IMECO TC4 Symposium and 12th Workshop on ADC Modelling and Testing*. http://www.imeko.org/publications/iwadc-2007/IMEKO-IWADC-2007-F136.pdf

[21] De Vito, L., Rapuano, S., & Slepieka, D. (2009, May). ADC standard harmonization: Comparison of test methods-Phase II. *In 2009 IEEE Instrumentation and Measurement Technology Conference* (pp. 1490–1495). IEEE. https://doi.org/10.1109/IMTC.2009.5168691

[22] Larsson, A., & Sonkusale, S. (2004, September). A background calibration scheme for pipelined ADCs including non-linear operational amplifier gain and reference error correction. *In IEEE International SOC Conference, 2004. Proceedings*. (pp. 37–40). IEEE. https://doi.org/10.1109/SOCC.2004.1362343

[23] IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters, in *IEEE Std 1241-2010 (Revision of IEEE Std 1241-2000)*, 1–139. https://doi.org/10.1109/IEEESTD.2011.5692956.

[24] Di Nisio, A., Giaquinto, N., Fabbiano, L., Cavone, G., & Savino, M. (2008). Improved static testing of A/D converters for DC measurements. *IEEE Transactions on Instrumentation and Measurement*, *58*(2), 356–364. https://doi.org/10.1109/TIM.2008.928878

[25] Albu, M. M., Ferrero, A., Mihai, F., & Salicone, S. (2005). Remote calibration using mobile, multiagent technology. IEEE Transactions on Instrumentation and Measurement, *54*(1), 24–30. https://doi.org/10.1109/TIM.2004.838139

[26] Berrani, S., Yachir, A., Djemaa, B., & Aissani, M. (2018, October). Extended multi-agent system based service composition in the Internet of things. *In 2018 3rd International Conference on Pattern Analysis and Intelligent Systems (PAIS)* (pp. 1–8). IEEE. https://doi.org/10.1109/PAIS.2018.8598503

[27] Peterek, M., & Montavon, B. (2020). Prototype for dual digital traceability of metrology data using X. 509 and IOTA. *CIRP Annals*, *69*(1), 449–452. https://doi.org/10.1016/j.cirp.2020.04.104

[28] Analog Devices, Inc. (2012). *AD8237 Micropower, Zero Drift, True Rail-to-Rail Instrumentation Amplifier* [Data sheet]. https://www.analog.com/media/en/technical-documentation/data-sheets/AD8237.pdf

[29] Analog Devices, Inc. (2021). *AD4630 24-Bit, 2 MSPS, Dual Channel SAR ADC* [Data sheet]. https://www.analog.com/media/en/technical-documentation/data-sheets/ad4630-24.pdf

[30] Analog Devices, Inc. (2020). *AD4682/83 Pseudo Differential Input, 1 MSPS/500 kSPS, Dual, Simultaneous Sampling, 16-Bit, SAR ADCs* [Data Sheet]. https://www.analog.com/media/en/technical-documentation/data-sheets/ad4682-ad4683.pdf

[31] Infineon Technologies AG. (2020). *CY8CKIT-059 PSoC® 5LP Prototyping Kit with Onboard Programmer and Debugger* [User Manual].

[32] Analog Devices, Inc. (2019). *ADG888 0.4 Ω CMOS, Dual DPDT Switch in WLCSP/LFCSP/TSSOP* [Data Sheet, Rev. D]. https://www.analog.com/media/en/technical-documentation/data-sheets/ADG888.pdf

[33] Analog Devices, Inc. (2021). *AD7606C-18 8-Channel DAS with 18-Bit, 1 MSPS Bipolar Input, Simultaneous Sampling ADC* [Data Sheet, Rev. A]. https://www.analog.com/media/en/technical-documentation/data-sheets/ad7606c-18.pdf

[34] Analog Devices, Inc. (2018). *ADuM5020/ADuM5028 Low Emission 500 mW Isolated DC-to-DC Converter*. [Data Sheet. Rev. A]. https://www.analog.com/media/en/technical-documentation/data-sheets/ADuM5020-5028.pdf

[35] Vishay foil resistors, Alpha electronic, Powertron. (2020). *Ultra High Precision Resistors*. https://www.ieee.li/pdf/viewgraphs/ultra_high_precision_resistors.pdf

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