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Metrological Array of Cyber-Physical Systems. Part 7. Additive Error Correction for Measuring Instrument

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Abstract: Since during design it is impossible to use the uncertainty approach because the measurement results are still absent and as noted the error approach that can be successfully applied taking as true the nominal value of instruments transformation function. Limiting possibilities of additive error correction of measuring instruments for Cyber-Physical Systems are studied basing on general and special methods of measurement. Principles of measuring circuit maximal symmetry and its minimal reconfiguration are proposed for measurement or/and calibration. It is theoretically justified for the variety of correction methods that minimum additive error of measuring instruments exists under considering the real equivalent parameters of input electronic switches. Terms of self-calibrating and verification the measuring instruments in place are studied. *Copyright © 2015 IFSA Publishing, S. L.*

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1. Introduction

Certain amount of controlled parameters are compulsory measured during operation of any Cyber-Physical System (hereinafter CPS). Hereby, measuring circle traditionally consists of sensors, connection lines (CL), channels commutator, scale and ADC devices. Modern tendency of multiplex smart measuring systems (MSMSs) design is aspiration to unification based on the transformation of any physical signals into electric one [1-2]. They have well known advantages in transferring, transformation, storing, registration etc. The direct current voltage is mainly used for precise ADC construction among all variety of electric signals [3-4]. The most sensors output signals are of low level that leads to significant impact of the measuring circuit error additive component (EAC) (Fig. 1). This EAC is determined by residual parameters of CL, channels commutator, equivalent offset voltages and input currents and their drift of scale analog block and ADC [1-2, 5].

The task of multichannel measuring of low-level signals in the interchannel interference affect conditions and necessity to assurance of spark- and explosion safety demands is of particular importance, especially in oil and gas, energy and chemical industries [13-23].

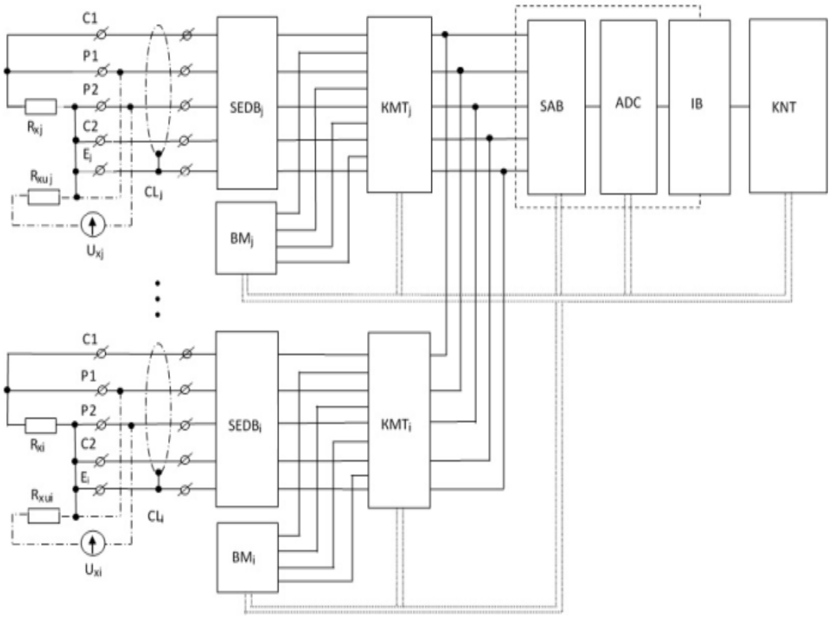

Fig. 1. Equivalent scheme of multichannel instruments for both self-generating and modulating sensors: KMT is a channel commutator; SEDB is an antispark and explosion damage barriers; SAB is a scale analog block; IB is an isolation block; BM is a block of measure; KNT is an instrument controller.

When isolating amplifiers are used for this purpose it results in not only substantial cost increase of the whole measuring circuit, but also it needs to correct errors in every measuring channel. Sometimes isolating amplifiers have not sufficient insulation rating for some important fields. It often demands to apply SEDBs in every measuring channel providing requirements of safety. It is necessary to emphasize that multichannel thermoelectric thermometers are complexity build because their prolonged lines are produced from expensive materials and it needs to provide automatic correcting the thermoelectric transducers cold junction temperature of every measuring channels [13-17].

In modern interpretation, measurement is considered as integral process of measurement information acquirement from object and further conversion to its processing, storing, transferring and usage trying to make retroaction at controlled technological objects [1, 5, 24].

Nowadays information measuring systems are usually built on high-level integrated electronic devices and the information technologies usage. As result, they became dispersed and their traditional calibration methods and devices lose sense [1, 5, 18-23].

Hence, it is reasonable to consider possibilities of smart electric devices to perform functions of automatic operative checking of CPS measuring circuits.

2. Shortcomings

There are many low-cost variable measuring instruments and transducers in the modern market. It significantly complicates the problem of their choice for some measuring tasks for CPS designing [3-5, 17, 18]. Simultaneously EAC automatic correction is one of the principal problems, which has usually the biggest weight among all other components of the error. This error value will depend considerably on the sensor type and measuring circuit configuration (Fig. 1). It can substantially change if the operation conditions of measuring device changed. To decrease this error various correction methods are used nowadays [1, 6-12]. Apparently, parameters of up-to-date intelligent ADC and DAC largely determine metrological properties of CPS.

If need measuring parameters of spark and explosive dangerous objects it is generally applicable isolated devices that have relatively not high precise (about some percent units) but high cost and need to use qualitative isolated block power supply units for every measuring channels. At the same time, every measuring channel is certainly ensured by automatic correction EAC means that increases its complexity and cost. MSMS’s spark dangerous or explosion safety is provided by SEDB located in every measuring channel (Fig. 1). It can lead the EAC value increasing by SEDB residual parameters and SAB input currents impact. Obviously when application the sealed contacts relay commutators, can provide the largest electric isolation rating. However, they are inherent in high and unstable residual voltage in operation conditions, which directly determined by EAC MSMS [3, 4, 13-16].

The principle disadvantage of known methods and instruments of MSMS developing is practical impossibility of their auto calibration in the operation places through impact of residual parameters of CL, SEDB and channels commutator.

The error additive component value of multichannel instruments determined by residual voltages of input measuring circuit and by the leakage currents of whole input electronic keys. So one of main urgent purpose of measuring instruments is developing the corrective self-calibration circuit. It enables to provide certain instruments metrological reliability, carry out operative check of processes running and ensure in operation conditions the verification of instruments as CPS-components.

If physical values sensors and measuring transducers (MTs) become widespread [1-2] an urgent task becomes the metrological providing optimization issue of such dispersed measuring systems. Considering modern trends of quality improvement, cost decreasing and relatively rapid obsolescence of electronic chips it can be possible to reach preset metrological reliability of MT for whole operation time. So try to minimize the EAC value, to the level less than one of least significant digit of CPS measurement reading. Regardless of their precision must be achieved adequate traceability [12-17]. In practice, the traceabilities in modern measuring systems are not principally ensured which required by normative documents through substantial labor intensity of metrological procedures [24-26].

3. Goal of the Work

The goal of paper is ascertainment of guidance to define boundary capabilities of the error additive component elimination of measuring instruments (devices, channels) at modeling stage.

4. Additive Error Auto Correction

Main principles of metrological assurance of MT development, production, testing and operation are regulated by number of standards. They determine general demands for measuring processes, devices, order of their usage and competence of testing and calibrating laboratories [24-26]. The basis of foregoing assurance is mathematical model of measuring instrument conversion functions and errors analysis at operating conditions. To correct errors the general and special measuring techniques are developed [5, 27].

4.1. Mathematical Model of Error

Generally, the error value $\Delta(X,\vec{Q},\vec{\zeta},t)$ depends on the quantity X of input informative signal. For its analysis, it is convenient to develop multinomial model [5, 28, 29]:

$$\begin{aligned}&\Delta_x(X,\vec{Q},\vec{\zeta},t)=\Delta_{0x}(\vec{Q},\vec{\zeta},t)+\delta_{Sx}(\vec{Q},\vec{\zeta},t)X+\\&+\varepsilon_x(\vec{Q},\vec{\zeta},t)X^2+\ldots=\overline{\Delta}_x(\vec{Q},\vec{\zeta},t,X)+\\&+\overset{0}{\Delta}_x(\vec{Q},\vec{\zeta},t,X)\end{aligned}\quad, \qquad (1)$$

where $\Delta_{0x}(.)$, $\delta_{sx}(.)X$, $\varepsilon_x(.)X^2$ are the additive, multiplicative and nonlinear error components respectively, and $\overline{\Delta}_x(.)$, $\overset{0}{\Delta}_x(.)=\Delta_x(.)-\overline{\Delta}_x(.)$ are the systematic and random error components respectively.

In general coefficients Δ_{0x}, δ_{sx}, ε_x are random values or processes dependent on vectors of $\vec{Q}$ parameters of the measuring circuit and $\vec{\zeta}$ errors factors, and they are independent of informative parameter *X*. Error systematic components always distort the measuring results. Therefore their establishment for amendments introduction seems to be one of major metrological problems. Unfortunately, universal method of systematic errors adjustment is not elaborated to a specified degree due to a number of methods, instruments and operating conditions [5, 27-29]. Systematic errors are considered expelled if they or sum of their non-expelled residue values don't exceed the half of the decimal digit unit which has one least significant figure of allowed error Δ_{al} of measuring result [5, 28, 29]. Forecasting of errors time drift demands conducting of complex research in operation conditions of particular measuring instruments and is not realized practically.

On the basis of (1) error systemic component leads to biased estimate of uncertainty area of result. At general methods applying try to avoid errors and/or to decrease their impact on obtained result. Special methods conjugates with the certain measuring algorithm, and their joint action can be implemented particularly depending on measuring realization [5, 27]. Methods of valid errors impact decreasing are widely applicable in measuring equipment, so it is reasonable to reveal the ways of measuring instruments quality ensuring. One of them is statistic minimization that consists in random errors impact decreasing and is widely utilized in transducer design [5, 27-29].

Errors auto correction with spatial separation of measuring channels and channels of correction is based on the measurement invariance principle and has to cover as many additional channels of correction as the number of destabilizing factors exists [5, 27]. However, this method is effective only at impact decreasing of mentioned factors. Moreover, it is compulsory to know dependence of MT errors on these factors and, ultimately, to appreciate of their impact actions on the certain (additional) units.

4.2. Limiting Capabilities Analysis of Systematic Errors Correction Methods

Let consider limiting capabilities of auto correction methods if correction and measuring channels are inherent in time division that is simplest in realization. In practice, MT's conversion function is submitted as:

$$y = KX + \Delta_{0x} = K_H(1+\delta_{Sx})X + \Delta_{0x}, \qquad (2)$$

where δ_{Sx}, Δ_{0x} is the multiplicative error (ME) coefficient and EAC MT respectively, X is the measuring value, K, K_H are the MT's conversion coefficient and their nominal value respectively.

Iterative method is apparently attractive due to its realization simplicity. Correction algorithm consists in step-by-step specification of the MT output signal y_i with help of precise inverse transducer DAC [5, 27]. The first corrected value of the conversion result y_i is given with consideration of members of second infinitesimal order:

$$y_1 = K_H X\left[1-\delta_{SM}+(\delta_{Sx}+\delta_{SM})^2\right]+ \\ +K_H\left(\Delta_{12M}-\Delta_1\delta_{SM}\right) \qquad, \qquad (3)$$

where R_X, R_{K1}, R_{LZ} are the measuring source internal resistance, closed key S_1 resistance of input switch and CL resistance respectively, I_{B1}, I_{C1} are source and drain electrodes inverse current of S_1 key, I_{B2} is source electrode inverse current of input S_2 key, I_{XZ} is MT input current, $I_{B123}=I_{B1}+I_{B2}+I_{B3}$, $I_{B12}=I_{B12}+I_{B12}$, R_{K2}, R_{SM} are closed key S_2 resistance of input switch and DAC output resistance respectively, I_{C2} is drain electrode inverse current of input switch S_2 key, X_M, y_i are DAC and MT output signal respectively, $\Delta_{12M}=\Delta_1- \quad -\Delta_2-\Delta_M$, $\Delta_1=\Delta_{0x}+I_{C1}R_X+I_{B123}(R_{K1}+R_{SM})$, $\Delta_2=\Delta_{0x}+I_{C2}R_{SM}+(I_{B12}+I_{SZ})(R_{SM}+R_{K2})$, δ_{SM}, Δ_M are DAC's ME coefficient and EAC respectively, y_i is calculating block output signal for step i iteration.

Analysis of (3) shows just after the first iteration, the measuring result error is practically determined by DAC errors. Furthermore, it is noticed the impact influence of EAC Δ_{12} difference, which is specified by configuration change of the MT input measuring circuit, and this configuration's value can exceed EAC value of the DAC precision. If the DAC error is significantly less than MT error then at the first iteration the measuring result code doesn't depend on ME MT $y_2 = K_H\left[X(1-\delta_{SM}-\delta_{SM}^2)\right]+K_H\Delta_{12M}(1-\delta_{SM})$. Practically it eliminates the need for following specification of measuring results, and EAC remains unchanged comparing with the first iteration result.

The realization simplicity of reference measures method promoted to its dissemination at ADC and electric measuring instruments auto calibration. If the transform function is described by (2), and dimension of the certain measures is equal to zero then the measuring result appears in three cycles at alternate measuring of signal X, zero signal and standard measure X_0. It is defined from the system of three equations with three unknown quantities X, Δ_a , δ_{Sx} [5, 27]:

$$\begin{cases} y_1 = K_H X(1+\delta_{Sx})+\Delta_1 \\ y_2 = \Delta_2 \\ y_3 = K_H X_0(1+\delta_{Sx})+\Delta_3 \end{cases}, \qquad (4)$$

where $\Delta_1 = I_{C1}R_x+(I_{B123}+I_{SZ})(R_x+R_{K1})+\Delta_{0x}$ is the EAC for measuring signal X, I_{C1}, I_{B1}, I_{C2}, I_{B2}, I_{C3}, I_{B3} are the drain and source electrodes inverse current of S_1, S_2, S_3 key of input switch respectively, $\Delta_2=\Delta_{0x}+I_{C2}R_{01}+ \quad +(I_{B123}+I_{SZ})(R_{01}+R_{K2})$ is the EAC for measuring zero signal, $I_{B123}=I_{B1}+I_{B2}+I_{B3}$, R_{K1}, R_{K2}, R_{K3} are the resistance of closed key S_1, S_2, S_3; R_x, R_{01}, R_0 are the internal resistance of measuring signals circuit X, zero and measure X_0 respectively, $\Delta_3=(I_{B123}+I_{SZ})(R_0+R_{K3})+ \quad +\Delta_{0x}+I_{C3}R_0$ is the EAC for measurement signal of reference measure X_0.

The value of measured quantity X is determined from the system (4):

$$X = X_0\frac{y_1-y_2}{y_3-y_2}\left(1+\frac{\Delta_{32}}{X_0}\right)-\frac{\Delta_{12}}{K}, \qquad (5)$$

where $R_{K12}=R_{K1}-R_{K2}$, $R_{K32}=R_{K3}-R_{K2}$, $\Delta_{12}= \quad =(I_{C1}R_x-I_{C2}R_{01})+\left[(R_x-R_{01})+R_{K12}\right](I_{B123}+I_{SZ})$ is the EAC difference for the first and the second measuring cycles, $\Delta_{32}=(I_{C3}R_0-I_{C2}R_{01})+\left[(R_0-R_{01})+R_{K32}\right](I_{B123}+I_{SZ})$ is a difference for the third and the second measuring cycles.

Expression (5) analysis shows that uncorrected AEC Δ_{12} and ME $\Delta_{32}X/X_0$ values at similar conditions, is determined by difference of internal resistances of measured R_x and reference signals R_{01}, R_0, and by residual parameters of input commutator. In practice, the resistance R_x of measuring signal source can change from zero to several hundred Ohm. For multipurpose commutative elements of parameters values $I_{Ci}\approx I_{Bi}=10$ *nA*, $\Delta I_{Ci}\approx\Delta I_{Bi}=1$ *nA*, $R_{Ki}\leq 50$ Ohm; $\Delta R_{Ki}\leq 5$ Ohm, in the normal operation conditions and under circumstance $R_x\leq 200$ Ohm, $R_0\leq 18$ Ohm, $R_{01}\leq 100$ Ohm the uncorrected error value caused by keys residual parameters can reach ±10 µV.

For electronic commutators at temperatures close to high operation limit the change of error drops to few tens of microvolt when our practical investigations are implemented. So even when MT parameters and reference measures values are invariable at the correction process duration, the uncorrected error value compared to the reference measures method depends significantly on difference of signals sources resistance of measured and correction channels, and it sufficiently changes with temperature while operating.

If test methods implements it is need several measuring cycles, which signals are formed without cutoff of measured quantity. It enables to conduct measurement not losing the obtained information [5, 27]. While measuring electrical quantities and realizing the additive and multiplicative tests (at considering the residual parameters of commutative elements and AEC of multiplicative test formation block (MTFB), the measuring result is received in four steps. These results in each of four steps y_1, y_2, y_3, y_4 are saved:

$$\begin{cases} y_1 = KX + \Delta_1 \\ y_2 = K(X + X_0) + \Delta_2 \\ y_3 = KmX + \Delta_3 \\ y_4 = K[m(X + X_0)] + \Delta_4 \end{cases}, \quad (6)$$

where Δ_1, Δ_2, Δ_3, Δ_4 are the MT EAC summarized to their input values for every of four cycles. Under results processing of these conversions the measuring result is described by:

$$X = X_0 \frac{(y_3 - y_1)(1 - \Delta_{4231}/X_{0E})}{y_4 - y_2 - y_3 + y_1} + \frac{\Delta_{31}}{X_{0E}}, \quad (7)$$

where $\Delta_{4231} = (\Delta_4 - \Delta_2) - (\Delta_3 - \Delta_1)$, $X_{0E} = X_0 K(m-1)$, $\Delta_{31} = \Delta_3 - \Delta_1$, I_{C11}, I_{C12}, I_{C2}, I_{C3}, I_{B11}, I_{B12}, I_{B2}, I_{B3} are drain and source electrodes inverse current of input keys respectively, Δ_m is MTFB EAC, I_{sz} is MT inverse current, R_x, R_0, R_{K11}, R_{K12}, R_{K2}, R_{K3} are respective resistance of measuring source signal, additive test formation block and input switch closed keys.

As analysis of (7) clarifies the non-corrected EAC value is mainly determined by the source resistances of measured signal and connecting wires R_x and by the reverse currents of input commutator. Furthermore, the mentioned test signals method compared to the reference measures method makes impossible to reduce the errors. Then it needs to provide the wider dynamic measuring range for concluding about limited usage of test methods.

There are modern not expensive processors and other digital integrated circuits, therefore algorithm methods of improved precision are attractive. These methods consist in multi-stage conversion of algebraic sum of measured and one or more standard quantities. While linear approximating MT transforms function for ideal commutative elements, nominal measuring equitation is given as the certain conversion code relation. This relation is equal to dividing part of differences of conversion codes in the first and third N_1-N_3 steps and in the first and second N_1-N_2 steps, where N_1, N_2, N_3 are results conversion codes obtained correspondingly for such algebraic values of the input quantity $X+X_0$, $X-X_0$, X_0-X [5, 27]. The measuring result error is determined only by changing the reference voltage values [5, 27] and residual parameters of commutative elements:

$$\begin{cases} N_1 = K(X + X_0) + \Delta_1 \\ N_2 = K(-X + X_0) + \Delta_2 \\ N_3 = K(X - X_0) + \Delta_3 \end{cases}, \quad (8)$$

where Δ_1, Δ_2, Δ_3 EAC which added up at MT input on the first, second and third measuring conversion cycles respectively, $\Delta_1 = \Delta_{11} + \Delta_{12} + \Delta_{13} + \Delta_{14} + \Delta_{15}$ $\Delta_{11} = (I_{C13} - I_{B13})R_{k1}$, $\Delta_{12} = (I_{C24} - I_{B24})R_{k2}$, $\Delta_{13} = (I_{C57} - I_{B57})R_{k5}$, $\Delta_{14} = (I_{C68} - I_{B68})R_{k6}$, $\Delta_{15} = I_{SZ}(R_x + R_{k1} + R_{k2} + R_{k5} + R_{k6} + R_0)$, $I_{C13} = I_{C1} + I_{C3}$, $\Delta_{21} = (I_{C68} - I_{B57})R_{k7}$, $\Delta_{22} = (I_{C57} - I_{B68})R_{k8}$, $I_{B13} = I_{B1} + I_{B3}$, $I_{B24} = I_{B2} + I_{B4}$, $I_{C24} = I_{C2} + I_{C4}$,
$\Delta_2 = \Delta_{11} + \Delta_{12} + \Delta_{21} + \Delta_{22} + \Delta_{23}$,
$\Delta_{23} = I_{SZ}(R_x + R_{k1} + R_{k2} + R_{k7} + R_{k8} + R_0)$,
$\Delta_3 = \Delta_{31} + \Delta_{32} + \Delta_{13} + \Delta_{14} + \Delta_{33}$,
$\Delta_{31} = (I_{C13} - I_{B24})R_{k3}$ $\Delta_{32} = (I_{C24} - I_{B13})R_{k4}$,
$\Delta_{33} = I_{SZ}(R_x + R_{k3} + R_{k4} + R_{k5} + R_{k6} + R_0)$,
I_{C1}, ...,I_{C3}, I_{B1},...,I_{B3} are drain and source electrodes inverse current of input keys *S1*, …, *S8* respectively, R_{SZ}, R_x, R_0 are resistance respectively of MT input, measuring signal *X*, reference signal X_0 and CL, R_{K1}, ..., R_{K8} are resistance of closed key *S1*, … , *S8* respectively, I_{SZ} is MT input current.

For solutions of system (8) we receive after simple transformation:

$$X = X_0 \frac{N_1 - N_2}{N_1 - N_3}\left(1 + \frac{\Delta_1 - \Delta_3}{2KX_0}\right) - \frac{\Delta_1 - \Delta_2}{2KX_0} \quad (9)$$

This equation analysis shows that uncorrected AEC and ME values are determined only by dispersion of closed keys resistances and their reverse currents. If group of keys S1, ..., S4 and S5,.., S8 are located in a same integrated microcircuit then experimentally determined dispersion of parameters values is not more than few percent [5, 27]. For mentioned keys parameters and their dispersion no more ±2 % even at maximal operating temperatures the uncorrected AEC value not exceed a few tenths of microvolt, and uncorrected value of ME coefficient when X_0=*1 B* is less than $\pm 10^{-5}$ %.

Advantages of algorithm methods include the possibility to provide invariance to MT conversion function without complication of measuring circuit, and only by conducting additional transformation into algebraic code ($-X-X_0$) [27]. Simultaneously uncorrected AEC and ME values must not exceed abovementioned values [27]. There exists sufficient impact of the error due to discreteness of transformed codes presentation N_1, ..., N_4. Therefore it seems necessary to choose $X<X_0$ that results in narrowing of MT measuring range.

General algorithm methods drawbacks include both measuring period and range expansion that restricts practical implementation.

4.3. Limiting Capabilities Analysis of Errors Correction Special Methods

Special correction methods of error systematic component include such ones as substitution, error compensation by sign, input quantity inverting, transposition and symmetrical observation [5, 27].

The peculiarity of these methods realization consists in necessity to change the measurement scheme configuration performed by commutators. Their residual parameters ultimately determine the quality of systematic errors correction. The transposition method has rare practical applying because it employ to correct conversion coefficients of double-channel balancing MT. Symmetrical method is occasionally available in practice as is correct only for linear changes of systematic error.

To realize substitution method in digital form is necessary application of multivalued code-controlled measure (CCM) and multiply valued MT. In the first cycle, the measuring quantity X measured by MT and obtained transformation result code $N_x = k_{ADC}\left[X + \Delta_{0x1}\right]$, where $\Delta_{0x1} = I_{B1}R_x + \left(I_{SZ} + I_{C12}\right)\left(R_{k1} + R_x\right) + e_{SZ} + {}$ ${} + I_{B1234}R_{k2}$ is equivalent to AEC value at X quantity measuring cycle. In the second cycle the reference quantity $X_0(N_x/N_m)$ should connect to the MT input and the code $N_{xn} = k_{ADC}\left[X_0\left(N_x/N_m\right) + \Delta_{0x2}\right]$ obtained, where k_{ADC} is ADC MT conversion coefficient, $\Delta_{0x2} = e_{SZ} + e_M + I_{B2}R_M + \left(I_{SZ} + I_{C12}\right)\left(R_{k2} + R_M\right)$, R_{k1}, R_{k2} are resistance of pair closed keys of both measuring and reference values respectively, I_{B1}, I_{C1}, I_{B2}, I_{C2} are drain and source electrodes inverse current of every closed pair input keys accordingly, e_{SZ}, I_{SZ} are bias voltage and input current, e_M is AEC which transforms into CCM input, $I_{C1} = I_{C1} + I_{C2}$, R_M is CCM output resistance, $I_{B123} = I_{B1} + I_{B2} + I_{B3}$.

On the assumption that two codes are equal each other the measured quantity value X is determined as:

$$X = X_0 \frac{N_0}{N_m}\left[e_M + I_{SZ12}R_{MX21} + I_{B2}R_M - I_{B1}R_x\right], \tag{10}$$

where $R_{MX} = R_M - R_x$, $R_{MX21} = R_{MX} + R_{k21}$, $R_{k21} = R_{k2} - R_{k1}$, $I_{SZ12} = I_{SZ} + I_{C12}$.

Analysis of equation (10) by means of substitution method demonstrates that corrected AEC value depends on AEC of CCM, source's signal resistance R_x and keys residual parameters of both input commutators.

If carry out digital measuring of direct current electrical quantities it is not usually succeeded to change measuring circuit that enables systematic error to maintenant their stable value but opposite sign. Therefore the error compensation by the sign method isn't practically used. However it is easy to fulfil inverting of the input signal. The structure of such MT includes compulsory polarity switch (PS), and the measuring result N_x is calculated as algebraic sum of codes N_1 and N_2 conversion under opposite polarity of the input signal. It enables to correct not only AEC but also some parts of MT polynomial approximation of conversion function [5, 27-29]. Indeed measuring results codes under positive $N_1 = \left(X + \Delta_{0x1}\right)k_{ADC}$ and negative $N_2 = \left(-X + \Delta_{0x2}\right)k_{ADC}$ polarities of the measured quantity:

$$N_x = 2k_{ADC}X + k_{ADC}\Delta_{0x12}, \tag{11}$$

where k_{ADC} is ADC MT conversion coefficient, e_{SZ}, I_{SZ} are bias voltage and input current, R_{k1}, R_{k2}, R_{k3}, R_{k4} are resistance of closed keys accordingly S1, …, S4 PS, I_{B1}, I_{C1}, I_{B2}, I_{C2}, I_{B3}, I_{C3}, I_{B4}, I_{C4} are drain and source electrodes inverse current of every keys pair of PS respectively, R_x is measuring signal source inner resistance, $I_{B14} = I_{B1} + I_{B2} + I_{B3} + I_{B4}$, $I_{C14} = I_{C1} + I_{C4}$, $\Delta_{0x1} = e_{SZ} + \left(I_{SZ} + I_{C14}\right)\left(R_{k12} + R_x\right) + I_{B14}R_{k2} + I_{B13}R_x$ is AEC for some polarity of measuring voltage, $R_{k34} = R_{k3} + R_{k4}$,
$\Delta_{0x2} = e_{SZ} + \left(I_{SZ} + I_{C14}\right)\left(R_{k34} + R_x\right) + I_{B14}R_{k3} + I_{B24}R_x$ is AEC for the opposite polarity of measuring voltage,
$\Delta_{0x12} = \Delta_{0x1} - \Delta_{0x2} = \left(I_{SZ} + I_{C14}\right)\Delta R_{1234} + \left(I_{B13} + I_{B24}\right)\Delta R_{12} + {}$ ${} + \left[I_{B13} - I_{B24}\right]R_x$ is corrected AEC value,
$\Delta R_1 = R_{k1} - R_{k2}$, $\Delta R_{1234} = R_{k12} - R_{k34}$,
$I_{B24} = I_{B2} + I_{B4}$, $I_{B13} = I_{B1} + I_{B3}$, $R_{k12} = R_{k1} + R_{k2}$,
$I_{B24} = I_{B2} + I_{B4}$.

Analysis suggests that corrected AEC Δ_{0x12} is determined only by keys parameters dispersion. At usage of integrated microcircuits with ordinary dispersion parameters that not exceed tenths of per cent [3-4, 6-7], AEC value can drop more than two orders of magnitude in comparison with other considered methods [5, 27-29]. Input signal inverting method allows to decrease the MT nonlinearity error due to elimination of pair powers members of general transform function.

4.4. Automatic Error Correction Methods Usage

Small value of uncorrected error is promoted the introduction of the input signal inverting method in the nested-chopper technique amplifiers and chopping ΔΣ ADC circuits.

In these nested-chopper amplifiers both the main and additional pairs of choppers has been applied. Additional pair of choppers operated at a much lower frequency (several tens of Hz) than the other original pair (several tens of kHz). This technique allows to reduce the effects of low-frequency interference and noise, including $1/f$ noise, offset and offset drift and cross-talk of the mains to equivalent voltage level about 100 nV [7]. In this case, only nested-chopper amplifier additive error can be reduced.

Chopping ΔΣ ADC inherent in adequate performance: the offset error specification of ADC is ±0.5 μV with drift ±5 nV/°C that is practically immeasurable [30]. But it has not decrease AEC whole measuring circuit including CL, SEDB and channel commutator.

Decentralized MTs are applicated for data transmission in the network. To ensure reliability of MT at low-cost system realization, the major efforts are concentrated on optimal MT design. Widespread MT use in control desks and panels of manufacturing processes supervision requires high temporal and temperature stability. Attention should be paid the duration of stable continued work without adjustment accompanied with extra difficulties and expenses [31]. Moreover, to decrease costs and to raise production efficiency the maximal possible structure simplifying is recommended.

The considered method of analog-to-digital quantity conversion at embodied technical MT characteristics is realized by choosing type and range of measured quantity especially inherent in direct current signals at the input. These include e.m.f., current or its voltage, especially of small values (f.i., output electrical signals of temperature sensors). To converse precisely current signals into code, the application of input signal inverting method is proposed [31].

Conducted errors analysis of the operation of serial devices A565 and CR7701 evidences the next. At MOS transistor applying as polarity switch and at converting direct current signals from sources (of inner resistance not higher than 1 kOhm) connected to MT input, the corrected value of AE no exceeds hundred nanoamperes (Fig. 2). In operation conditions MT errors are several times higher than limits of permitted values established for normal conditions. Then methodical error also can affect the data. It is specified by ratio of MT input resistance to input resistance of signal source and connecting lines.

Fig. 2. Front view of universal digital multichannel measuring and signaling device CR7701.

Peculiarities of the digital measuring devices structure, designed to operate with industrial MTs, are given below. It is low input signals level, high noise power of normal and common types, linearization of transform function, necessity of cold junctions compensation, the significant errors at overheating of resistive transducers by measuring current, providing of invariance of measuring result to this current value, and also resistances of three and four terminal connection line. The same concerns high temperature action and enhanced drift metrological reliability, especially at MT operating in energetics and chemistry.

Therefore MTs are produced with AEC auto and digital linearization of conversion function. The sufficient interference reducing is achieved by averaging methods applied in ADCs and galvanic division of analog and digital units.

Company “MuckachivPrylad”, Ukraine, produces universal MT control desk of CR7701 type intended to gauge direct current, e.m.f. and direct current voltage, temperature (with a number of uniform primary transducers), other physical quantities transformed in aforementioned signals [31] (Fig. 2). It is characterized by the next characteristics: permitted coverage interval of relative error not higher ±(0.1...0.2) %, operating temperatures from 5 to 50 ^{0}C, permitted coverage interval of additional relative error not higher than a third part of basic measurement error, operation time without maintenance less than 5 000 hours [31].

4.5. Intelligent Data Acquisition System Error Correction in Working External Conditions

Nevertheless, both the CR7701 type devices and the devices based on the ADC chip make it possible to the AEC correction covering of the part measured circuit. Obviously, we deal only with AEC of processing device. In practice, generally quite long CL connects the industrial devices with the sensors, where due to contact phenomena and temperature gradients the e.m.f. can appear. This AEC is caused also the voltage drops caused of the leakage isolation currents flowing from the neighboring robust electric sources.

In the operation conditions, the secondary devices are the part of the measuring circuit, which includes except them the primary measuring converter and the CL. If it large length that can bring into the measurement result quite considerable, and what is especially important, uncontrolled errors. These errors are invoked as well by the contact e.m.f., which can occur in the wires junctions, and by CL resistance change, and as well inducted the normal and common type interferences from the near robust electric equipment and also if CL isolation resistance worsening, etc. The previous analysis shows, that AEC which occurs in CL are the low-frequently and slowly changeable in time. Therefore, the measurement impact in first approximation can be considered as the additive character and utilize the input signal inverting method for their correction and placement of the polarity switch as close as possible to the sensor exit (Fig. 3).

A flip-flop switch (FFS) takes place as closer to the sensor output as possible to correct the AEC of measuring signal conversion circuit. The quantity of the CL wires rises to five. For the measurement result determination it is necessary to take into account the additional EACs caused by the leakage currents of the FFS switch control electrodes through flow across its isolation resistances R_{is1}, R_{is2} and the resistance of one of the R_{LZ} CL wires. The measurement result in this case is found as a subtraction of two codes:

$N_{11} = k_{ADC}\left[\left(U_X + \Delta_{XL1}\right)k_1 + \Delta_{0x}\right]$ and
$N_{12} = k_{ADC}\left(k_1 \Delta_{XL2} + \Delta_{0x}\right) - k_{ADC} U_X$

$$N_1 = N_{11} - N_{12} = 2k_{ADC}\left[U_X + \left(I_{i1} - I_{i2}\right)R_{CL}\right] \qquad (12)$$

where I_{i1}, I_{i2} are respectively the leakage currents flowed through the isolation resistance of control electrodes of the first and second key pairs, $\Delta_{XL1} = \Delta_1 + \Delta_{CL} + I_{i1}R_{CL}$, $\Delta_{XL2} = \Delta_2 + \Delta_{CL} + I_{i2}R_{CL}$, Δ_{CL}, $I_{i1}R_{CL}$, $I_{i2}R_{CL}$ are equivalent AECs, that occur in the CL resistance and because of the I_{i1}, I_{i2} leakage current flowing through the R_{lZ} resistance of the CL wire (Fig. 3).

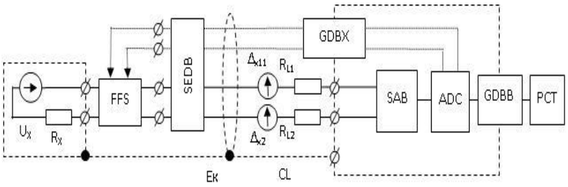

Fig. 3. The digital voltmeter structure with auto additive error correction of measuring circuit.

As correlation analysis of (12) suggests, the uncorrected error value is determined by the subtraction of FFS entrance switch control electrode leakage currents. In order to reduce the EAC uncorrected value it is necessary to provide the high resistance of the input polarity switch control circuit isolation. If the devices must operate in the aggressive conditions and at high humidity, we try to supply the high isolation resistance. We should note now that the residual leakage currents affects the uncorrected EAC value. The leakage currents scatters both for integrated chips that the implement as the polarity switch and their control electrodes circuit is not exceed ±20 % of the control electrode leakage current value [3-4]. For example, when the typical minimal value of the isolation resistance in the digital devices is upper than 40 MOhm, the control voltage value 15 V and the maximal resistance value of the connection line does not exceed 200 Ohm, the uncorrected AEC is not more than a few microvolts that satisfies preferably.

We should stress that this technical proposed decisions to be based on some improvement of the integrated ADCs chip.

Analysis of conversion technique has suggested that in the electric measurements means to support the standardized metrological characteristics the periodic calibration is made. To correct the multiplication error changes it is expediently to change the digital voltmeter structure by connection of precision code controlled voltage measure (CCVM) with input switch. As a result, we obtain a structure of a differential voltmeter, whose metrological opportunities can be controlled permanently at the exploitation place by periodic change of a set CCVM block on a metrological tested one.

Evidently, we should manufacture CCVM as a separate integrated chip with the displaced means of some error component correction in the exploitation conditions after an additional measurement method and with removing of the destabilized factors influence after the development methods.

It is possible to protect such a voltage measure from influence of the electric-magnetic fields and radio transmission with help of screening and from humidity as well as harmful activity of the aggressive chemical compounds by hermetization. If the code-controlled voltage measure to be as a small-sized portable block the principal opportunities of remote metrological verification of the measurement instruments and of considerable increasing of metrological reliability to any apriority establishing level are created.

It is reached by periodic metrological verifications of the portable CCVM blocks. Taking into account their particular parameters in the microprocessor block of measurement the device remote calibration can be realized.

5. Conclusions

1. The analysis of general and specific methods for the measurements accuracy improving suggests that the theoretical minimum value of corrected additive component error can be achieved if the input measuring circuit is almost unchanged for the measurement and correction channels. The input signal inverting method is able to provide it only through the input electronic switch application for measuring signals of two polarities.

2. The corrected value of additive error component is determined by only dispersion parameters of pairs electronic keys of input polarity switch. Firstly it is defined by the resistance difference of both pairs of switch polarity closed keys and their reverse currents. To reduce error value is advisable determining the keys similar parameters impact.

3. It is advisable to locate switches polarity as close as possible to the sensors, and to carry out galvanically isolated control and power circuits in order to correct in place the additive error component of measuring channels especially with spark and explosion protection.

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