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Metrological Array of Cyber-Physical Systems. Part 11. Remote Error Correction of Measuring Channel

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Abstract: The multi-channel measuring instruments with both the classical structure and the isolated one is identified their errors major factors basing on general it metrological properties analysis. Limiting possibilities of the remote automatic method for additive and multiplicative errors correction of measuring instruments with help of code-control measures are studied. For on-site calibration of multi-channel measuring instruments, the portable voltage calibrators structures are suggested and their metrological properties while automatic errors adjusting are analysed. It was experimentally envisaged that unadjusted error value does not exceed ± 1 μV that satisfies most industrial applications. This has confirmed the main approval concerning the possibilities of remote errors self-adjustment as well multi-channel measuring instruments as calibration tools for proper verification. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Cyber-physical system, Metrological assurance, Multi-channel measuring instrument, Remote errors correction and verification, Code-control voltage measure.

1. Introduction

Cyber-physical systems (hereinafter CPSs) are deemed to be an integral part of manufacturing systems, factories, machinery, test facilities, moving objects, vehicles etc. These facilities typically utilize thousands of physical phenomena, whose parameters are constantly changing.

Each CPS is comprised of dispersed hardware components and computer software, intended to obtain information about the progress of physical processes in controlled facilities, as well as its storage, transmission, processing and production by control signals. Especially it is needed information on the measured values including the location, value, speed changes, etc.

The measurement data, received from controlled objects, would be characterized by the set of metrological parameters. The measuring channels distribution in space, permissible changes in a wide range of operating parameters and inevitable degradation of measuring circuits parameters result in a significant deterioration of the CPS measuring channel performance. Thus, an operative metrological maintenance of measuring channels becomes important [1].

2. Shortcomings

CPS measurement data accumulation and processing is performed by means of multi-channelled measuring instruments (further MCMIs) that consists of measuring sensors, communicating lines (further CLs), channel commutators (further CCs) and measuring instruments (further MIs) (Fig. 1). The current trends of measuring systems design seems to be the implementation the measuring transducers that transfer the received signals into electrical form aiming the direct computing [2-3]. Whereby, digital measuring information could be obtained with help of the certain methods of processing, transmission, storage, reverse transformation for the control function for CPS units.

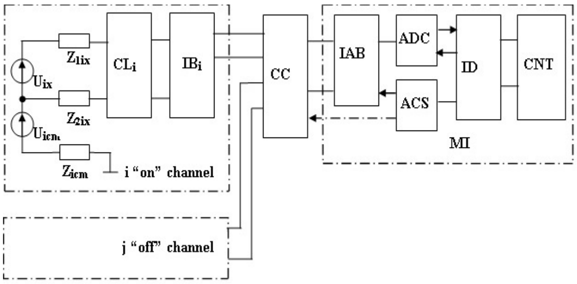

Fig. 1. Functional scheme of modern multi-channel measuring instruments: CC is the channel commutator; IB is the intrinsic safety barrier; CL is the communicating lines; IAB is the input amplification block; ID is the isolation device; ACS is the analogue control circuit; CNT is the instrument controller.

The low level of output sensors signals require input amplification block (further IAB) that scales the previously mentioned signals to normal level for ADC operation and simultaneously converts them in a digital code necessary for MI controllers.

Measurements in sparkproof operating conditions and in dangerous environments envisage implementtation of some specific techniques. First, the inner safety barriers must applied at the output sensors of each measuring channel, and the analogue circuit of MI has to be isolated from the digital one (Fig. 1) [4-7]. The interference values often exceed the signal parameters of CC channels. So standard signal transducer (further SST), isolated amplifier (further IA) or isolation device (further ID) it usually applied. The systematic errors that have both significant additive and multiplicative components emerge in measuring circuit of such data acquisition systems (further DASs). Error values increase in DASs with isolated channels; therefore, it is difficult to ensure their operation by considerable time at the certain temperature drift [7-12].

To correct the errors of CPSs, the calibrators of electrical quantities directly connected to measuring channel input instead of sensors are mainly applied. However, these calibrators are large, heavy, and quite expensive; so their implementation is complicated [13]. To provide the remote automatic adjustment, currently the CPS measuring channels with embedded devices are designed. It upraises a problem of automatic errors correction of operating calibrators that have to be inexpensive due to their wide use.

3. Aim of Work

The aim of this article is the development of theoretical basis and practical guidance for providing the high accuracy of multi-channelled measuring instruments in operating conditions.

4. Theory and Applied Researches

The MCMI scheme (Fig. 1) for measured object without spark and explosive environments and at the common mode voltage lower than the CCs chip breakdown voltage (10 V), is studied. So while gauging spark and explosive objects, it should be used the isolation blocks (further IBs) on the sensor outputs of every measuring channel. It recommends an extra electrical isolating the sensors and MCMI for particular dangerous objects [4-7]. For this purpose, the magnetic, capacitive, or optical means are generally applied in the measuring circuits that considerably decrease the error values at variable operating condition.

The emerging ground loop can be quite large (up to several kilo ampere) that causes the common mode voltage up to hundreds of volts. Its values especially increase with CL length between the ground points of both measured facilities and MCMI. Another source of common mode voltage can be leakage currents of power networks that pass through measuring equipment insulation for ground loops measured object. That application point of common mode voltage to the sensor is generally unknown. To exclude above-mentioned drawbacks the relays as CC with switching function "before turning off" for large common mode voltage, can be used. Such scheme practical application is inherent in a significant (up to several millivolts) additive error component (further AEC) caused by contact EMF at temperature drift (up to ten $\mu V/K$). Thus, MCMI structure seems to be similar to the design shown in Fig. 1. To reduce significantly errors values caused by CLs and CCs, SST converters or IA are currently applied.

Three-wire sensors connection, and screening the CLs as well as MCMI analogue part substantially decreases the common mode voltage [2, 7, 14]. Then the block diagrams of MI significantly differ from MCMI in Fig. 1.

4.1. Metrological Properties Analysis of Classic Multi-Channel Measuring Instruments

Output sensors signals are submitted to the CC inputs through IB (if necessary) and CL. In addition to the measuring signal U_X, every measuring channel is inherent in own common mode voltage. A differential circuit of IAB is applied for reducing the common mode voltage affects (Fig. 2).

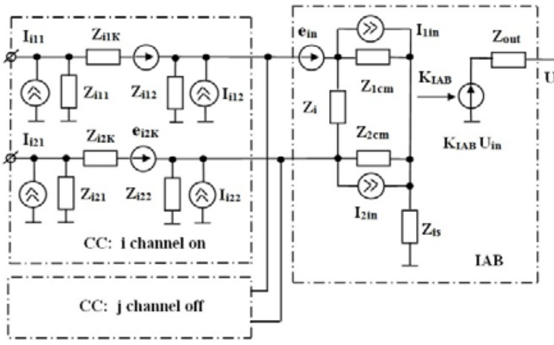

Fig. 2. Equivalent scheme of channel commutator and input amplifying block.

Relegated to MCMI input the measured voltage U_{ixn} in the "i" on-channel is presented below (at the known common mode voltage U_{icm} applying point):

$$U_{ixn} = U_{ix}(1+\delta_i) + e_{ie} + U_{iI} + U_{ixc} + U_{ijx} + U_{ijxc}\ , \qquad (1)$$

where U_{ix} is the output sensor voltage in i on-measuring channel, $e_{ie}=e_{iCL}+e_{iIB}+e_{iCC}$ is the equivalent input offset voltage, $e_{iCL}=e_{1iCL}+e_{2iCL}$, $e_{iIB}=e_{1iIB}+e_{2iIB}$, $e_{iCC}= +e_{1i\kappa}+e_{2i\kappa}$, $e_{1i\kappa}$, $e_{2i\kappa}$ is the residual voltage of the first and the second on-keys CC respectively (e_{iCC}=0 for MOS FET chip keys), $\delta_i=Z_{ixe}/Z_{\mathrm{in}}$, $Z_{ixe}=Z_{1ixe}+Z_{2ixe}$, $Z_{1ixe}=Z_{1ix}+Z_{1iCL}+Z_{1iIB}+Z_{1iCC}$, $Z_{2ixe}=Z_{2ix}+Z_{2iCL}+Z_{2iIB}+$ $+Z_{2iCC}$ is the total resistance between common mode voltage applying point and the first and the second IAB differential inputs respectively, U_{iI} is the equivalent error value caused by equivalent currents of both IAB differential inputs, U_{iec} is the equivalent error value caused by common mode voltage of "i" on-channel, U_{ijx} is the equivalent error value caused by the penetration of the measured voltages U_{jx} from other measuring off-channel, U_{ijxc} is the equivalent error value caused by the penetration of the common mode voltages U_{jxc} from other measuring off-channel.

AEC value U_{iI}, caused by equivalent currents of both differential inputs IAB, is estimated:

$$U_{iI} = U_{1iI} - U_{2iI} = I_{1e}Z_{1e} - I_{2e}Z_{2e}\ , \qquad (2)$$

where $I_{1e} = I_{1in} + I_{i11} + I_{12e}$, $I_{2e} = I_{2in} + I_{i21} + I_{22e}$ is the equivalent current values of both IAB differential inputs accordingly, I_{1in}, I_{2in} is the input current of both IAB differential inputs concordantly, I_{i11}, I_{i21} is the input reverse current of both CC "on" input keys at i channel respectively, $I_{12e} = \sum_{i=1}^{n} I_{i12}$, $I_{22e} = \sum_{i=1}^{n} I_{i22}$, I_{i12}, I_{i22} is the output reverse CC current for i on-channel, Z_{1e}, Z_{2e} is the equivalent common mode resistance of both IAB differential inputs accordingly, n is the number of measuring channels.

We can accept that value of the input and output common resistance of CCs approximately equal to each other: $Z_{i11}=Z_{i1}(1+\delta_{i11})$, $Z_{i12}=Z_{i1}(1+\delta_{i12})$, $Z_{i21}=Z_{i1}(1+\delta_{i21})$, $Z_{i22}=Z_{i1}(1+\delta_{i2})$, where δ_{i11}, δ_{i12}, δ_{i21}, $\delta_{i22} \ll 1$, δ_{i11}, δ_{i12}, δ_{i21}, δ_{i22} are the relative dispersion of the common mode resistance estimated for "i" CCs channel. This error can be determined in a few tens per cent. Taking into account the following values of ratios Z_{1ixe}, $Z_{2ixe} \ll Z_{in}$, Z_{1en}, Z_{2en}, the expression for the equivalent input resistances is defined:

$$Z_{1e} \cong \frac{Z_{en}Z_{eis}}{Z_{en}+2Z_{eis}}\left[1+\frac{b}{Z_{en}}\left(Z_{2ixe}+\frac{Z_{1ixe}}{a^2}\right)\right], \qquad (3)$$

$$Z_{2e} \cong \frac{Z_{en}Z_{eis}}{Z_{en}+2Z_{eis}}\left[1+\frac{b}{Z_{en}}\left(Z_{1ixe}+\frac{Z_{2ixe}}{a^2}\right)\right], \qquad (4)$$

where $Z_{en}=(Z_{1e}+Z_{2e})/2$, $Z_{en} = 0{,}5Z_{i1}Z_c/\left[(n+1)Z_c + Z_{i1}\right]$, Z_{1e}, Z_{2e} is the equivalent common mode input resistance accordingly, $Z_{1e} = 1/G_{1e}$, $Z_{2ec} = 1/G_{2ec}$, $Z_{eis}=Z_{is}+Z_{icm}$, Z_{is}, Z_{icm} is the common mode resistance of i on- measuring channel and isolation resistance of common measuring bus (measuring "ground") relatively MCMI grounding point respectively, $G_{1e} = 1/Z_{i11} + 1/Z_{1c} + \sum_{\mathrm{i=1}}^{\mathrm{n}}(1/Z_{i21})$, $G_{2e} = 1/Z_{i21} + 1/Z_{2c} + \sum_{i=1}^{n}(1/Z_{i22})$, Z_{i11}, Z_{i21} is the common mode input resistance for "i" on-channel, Z_{i21}, Z_{i22} is the common mode output resistance for i on-measuring channel, $a=Z_{eis}/(Z_{eis}+Z_{en})$, $b=a/(1+a)$, $Z_{1ixe}=Z_{1ix}+Z_{1iCL}+Z_{1iIB}+Z_{1iCC}$, $Z_{2ixe}=Z_{2ix}+Z_{2iCL}+Z_{2iIB}+$ $+Z_{2iCC}$, Z_{in} is the differential input resistance, Z_{1c}, Z_{2c} is the common mode input resistance of both IAB differential inputs respectively.

Considering the expressions (3) and (4), obtain the AEC U_{iI} caused by equivalent input currents:

$$U_{iI} \cong \Delta I_e Z_{en} b + 2I_{ein}\Delta Z_{ixe}\left(1+a^2\right)(b/a)^2\ , \qquad (5)$$

where $\Delta I_e=I_{1e}-I_{2e}$, $I_{ein}=(I_{1e}+I_{2e})/2$, $\Delta Z_{ixe}=Z_{1ixe}-Z_{2ixe}$.

Caused by common mode voltage U_{icm} at "i" on-channel after sequence of alterations, error U_{ixc}, is determined:

$$U_{ixc} \cong U_{icm}\frac{Z_{ixe}}{2Z_{isx}}(\delta_{ixe}+\delta_{ie}), \qquad (6)$$

where $Z_{ixe}=Z_{1ixe}+Z_{2ixe}$, $\delta_{ixe}=\Delta Z_{ixe}/(Z_{1ixe}+Z_{2ixe})$ is the relative dispersion of both total input resistance Z_{ixe} IAB, $\delta_{ie}=(Z_{1e}-Z_{2e})/2Z_{en}$ is the relative dispersion of both equivalent input differential resistances IAB, $Z_{isx}=Z_{icm}+Z_{is}+Z_{en}/2$.

Analysis envisages that error value U_{ixc} caused by common mode voltage U_{icm} inherent in additive and asymmetrical features and depends on both differential inputs resistances IAB (Fig. 2). For its reduction, one should increase the insulation resistance of the common bus IAB to the applying point of common mode voltage U_{icm}.

The equivalent error U_{ijx} caused by penetration to “*i*” on-channel measuring voltage U_{jx} from the all off-channels is equal to:

$$U_{ijx} = \sum_{j=1}^{n-1}\left(U_{jx}\frac{Z_{in}}{Z_{in}+Z_{jp}+Z_{jxe}} \right), \qquad (7)$$

where $Z_{jxe} = Z_{jx}+Z_{jCL}+Z_{jIB}$, Z_{jx}, Z_{jCL}, Z_{jIB} is the inner resistance of sensor, CL and IB at j off CC channel respectively.

The nature of this relative to the measured voltage in “*i*” on-channel error is additive. For its adjustment it can be applicable the known automatic methods. Analysis of (7) results in the following; the error of voltage U_{ijx} increases proportionally to the number of measuring channels n. For its reduction within the MCMI classical structure should choose the CC with a maximum high value off-resistances. However, this kind of MCMI accuracy improvement substantially limits imposed by the parameters of chip components. For example, if typical values are equal to $Z_{in} \simeq 10^9$ *Ohm*, $Z_{jp} \simeq 10^{12}$ *Ohm*, $Z_{in} \ll Z_{jxe}$, and the measured voltages values approximately equal to each other $U_{jx} \simeq U_{ix}$ weighting factor significance k_{ijx} drops down in the order of value: to $k_{ijx1} \cong 0.001$ at the number of measuring channels $n=2$, or to $k_{ijx2} \cong 0.01$ at number of channels $n=12$.

Threshold value of AEC U_{ijxc} interference caused by penetration of a common mode voltage U_{jcm} of all the other off-channels to the “*i*” on-channel, gives expression:

$$U_{ijxc} = \sum_{j=1}^{n-1}\left\{ \frac{U_{jcm}Z_{ixe}Z_{jp}}{2Z_{jcm}\left(Z_{jp}+Z_{ieci}\right)}\left[k_1\delta_{ixe}+k_2\delta_{ie}\right] \right\}, \qquad (8)$$

where $Z_{jp}=Z_{1jp}+Z_{2jp}$ is the “off” keys resistances of j CC off-channel, $Z_{ieci} = \frac{2Z_{jcm}\left(Z_{en}+2Z_{is}\right)}{2Z_{jcm}+Z_{en}+2Z_{is}}$, Z_{jcm} is the common mode resistance in j CC off-channel; $k_1 = \frac{2Z_{jcm}+Z_{en}+2Z_{is}}{Z_{jcm}+Z_{en}+2Z_{is}}$, $k_2 = \frac{2Z_{en}Z_{jcm}}{\left(Z_{en}+2Z_{is}\right)^2}$, $\delta_{ixe}=(Z_{1ixe}\ --Z_{2ixe})/Z_{ixe}$ is the relative dispersion of equivalent resistance between the applying point of common mode voltage and both IAB differential inputs.

Its analysis shows that the AEC value U_{ijxc} determined by asymmetries of input measuring circuits MCMI in “*i*” on-channel and input equivalent common mode resistances, depends on the number of n measuring channels. Indeed, equilibration of input measuring circuits is time-dependent. These schemes are symmetric for a particular object and measuring current circuit parameters MCMI in certain working conditions. However, while measuring circuit reconfigures or working conditions changes, this symmetry is broken. In practice, tend to reduce the AEC value U_{ijxc} ensuring sufficiently high insulation resistance Z_{is} of common bus IAB at applying point of common mode voltage U_{jcm}. Further minimization of this error value is possible automatically by AEC U_{ijxc} adjusting.

Analysis of Equations (1), (5)-(8) envisages that the MCMI AEC substantially depends on the number of n measuring channels. This is especially true for equivalent values of input offset voltage, input currents, input impedances IAB and resistances “off” keys CC. For the relay switches, the CC implementation can significantly diminish the equivalent input currents and resistances impact. However, the residual voltage relays significantly increases AEC value. The switching channel speed MCMI has to be small. If the electronic keys apply in the CC, located at the MCMI input, the keys residual voltages are eliminated only.

To diminish these errors components, is suggested to set the smart transducer with input IAB as close as possible to the sensor output [2, 7]. It virtually eliminates the errors caused to CL and CC parameters because output signals of such transducers are standard high-level electrical signals that can submitted straight to standard ADC inputs.

The problem of MCMI design significantly complicates when the common mode voltage U_{jcm} exceeds electric strength of CC keys. Three-wire sensors connecting and respectively reciprocal isolation of measuring channels are recommended for these errors appreciable minimization.

4.2. Analysis of Properties of Isolated Multi-Channel Measuring Instruments

The relative isolation of measurement channels is suggested due to several reasons. The first one is necessity to protect the MCMI electrical circuits of the measured object against spark and/or explosive damage (Fig. 3). Additionally it needs to connect IB to the every measuring line. The IB inner resistance value can reach hundreds *Ohms*. It could cause AEC value magnifycation due to passing the leakage currents through the mentioned resistance. F.i. under regulations, the insulation resistance of power networks has not been less than 40 *MOhm*. Then the passing leakage current I_p of grounded measuring object does not exceed 220 V / 40 MOhm ≤ 5 μA. This current can produce voltage drop $U_{ixiB}=I_p(Z_{ix}+Z_{iB})=10$ *mV* on the inner resistances ($Z_{ix} \approx Z_{iB} \le 1$ *kOhm*) of sensor and IB, which is considered as MCMI AEC.

Isolation for every measuring channel permits diminishing the impact of the potential difference that emerges between grounding points of measuring object and MCMI. These potential differences are generated by powerful sources due to the leakage currents passing through resistances of ground point and earth. Their value may reach hundreds of volts (electric transport, melting furnaces, converters) can cause these interferences. It is impossible to exploit switches in such conditions.

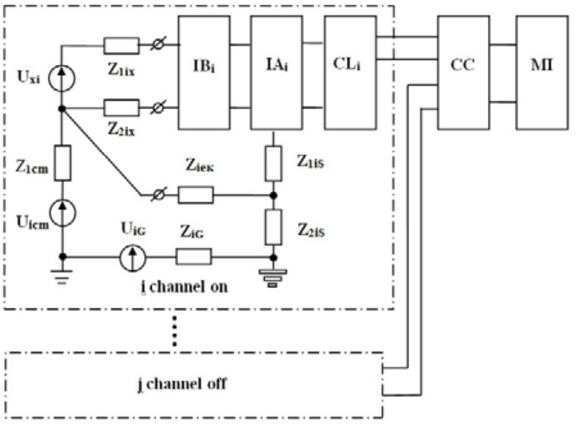

Fig. 3. Scheme of multi-channel measuring instruments with isolated channel.

To minimize the common mode interference, three-wired CL connecting sensors apply. The screen serves as a third wire, which protect two information CL lines between the sensor output and MCMI input (Fig. 3). By the sensor side this screen should be connected to the point of applying the common mode voltage if it available. Moreover, it needs to connect MCMI to the screen at the CL end. MCMI screen must have the high insulation resistance concerning the measuring circuit. The caused CL error significantly rises if CL length substantially grows. Therefore, SST implementation decreases the afore-mentioned error, owing to the low cost chip components [2-3]. Especially it is inherent in the isolated amplifiers. Output voltage U_{ixis} IA MCMI (Fig. 3) is high enough for direct interface with standard ADC. Then the relay keys can operate in CC unit. Output voltage expression U_{ixs} IA$_i$ is given:

$$U_{ixs} = (U_{ix} + \mathrm{e}_{iA\mathrm{e}} + U_{icA})k_{iA}(1+\delta_{iA}) + \\ +e_{ioA} + U_{ijxA} + U_{ijcA} + U_{ine}, \tag{9}$$

where $\mathrm{e}_{iAe} = \mathrm{e}_{iA} + \mathrm{e}_{iIB} + I_{iA}Z_{ixA}$, $Z_{ixA} = Z_{1ixA} + Z_{2ixA}$, $Z_{1ixA} = Z_{1ix} + Z_{1iIB}$, $Z_{2ixA} = Z_{2ix} + Z_{2iIB}$, e_{iA}, e_{iIB} is the offset voltage IA$_i$ and residual voltage IB$_i$ accordingly, $\delta_{inA} \cong Z_{ixA}/Z_{inA}$, I_{iA}, Z_{inA} is the input current and resistance IA$_i$ respectively, Z_{1iiS}, Z_{2iiS}, Z_{3iiS} is the isolation resistances between IA$_i$ input and output, common bus and screen IA$_i$ accordingly, $\delta_{inA} \cong Z_{ixA}/Z_{inA}$, $U_{ine} = I_{i11}Z_{iCL} + \left(I_{i12} + I_{in} + \sum_{j=1}^{n-1} I_{j12}\right)(Z_{1iCC} + Z_{iCL})$ is the equivalent output voltage IAB, e_{io} is the offset output voltage IA$_i$, U_{icA} is the equivalent input voltage of "*i*" on-measuring channel caused by equivalent common mode voltage $U_{ic} = U_{icm} + U_{iG}$, U_{ijxA} is the equivalent input voltage of "*i*" on-measuring channel caused penetration of measuring voltage U_{jx} other off-measuring channel, $U_{ijc\mathrm{A}}$ is the equivalent input voltage of "*i*" on-measuring channel caused penetration of equivalent common mode voltage $U_{jc} = U_{jcm} + U_{jG}$ other off-measuring channel, $\mathrm{e}_{ioA} = \mathrm{e}_{io} + \mathrm{e}_{iCL}$, Z_{iG}, U_{iG} is the resistance and voltage between grounding points of IA$_i$ and measuring object at "*i*" "on" measuring channel, k_{iA} is the IA$_i$ transducer coefficient.

Input equivalent voltage U_{icA} at "*i*" on-measuring channel, due to its equivalent common mode voltage U_{jc}, presents as:

$$U_{ixcA} = U_{ic}\frac{Z_{2ixe}}{Z_{icm} + Z_{iG} + Z_{3iis}} \cdot \frac{Z_{iek}}{Z_{2iis}} \tag{10}$$

Analysis of latter clarifies at minimization of error voltage value U_{ixcA} that should be provided firstly at small resistance Z_{iek} of screen and secondly by high value of the screen insulation resistance Z_{2iiS} concerning the measuring scheme. From comparing the latter equation and Equation (6) we conclude that the error value U_{icxA} caused by common mode voltage at "*i*" on-measuring channel is reduced in $Z_{iek}\,/\,Z_{2iiS}$ times. For example, it occurs if IA AD210 type Analog Devices is used and is provided the screen resistance $Z_{iek} \leq 10$ *Ohm* at ordinary values of insulation resistance $Z_{2iiS} \simeq Z_{3iiS} \simeq 240\ V\ /\ 2\ \mu A = 1{,}2\cdot 10^8$ *Ohm* [15]. Also, if select the common mode voltage $U_{ic} \leq 2500\,V$ equal to the maximum isolation voltage of the same IA type at $Z_{icm} + Z_{iG} \simeq 40$ *MOhm*, the equivalent input voltage is $U_{ixcA} \leq 2500(10/1.6\cdot 10^8)\cdot(10^3/1.2\cdot 10^8) \cong 41$ *nV*. The latter is negligible for most application cases.

Reduced to an IAB input equivalent voltage $U_{ij\mathrm{x}A}$ at "*i*" on-measuring channel caused by penetration of measured voltage $U_{j\mathrm{x}}$ all the rest *(n-1)* CC off-channels is unable to change it comparing with value of obtained from (7). Threshold AEC value U_{ijcA} caused by penetration of equivalent common mode voltage $U_{jc} = U_{jcm} + U_{jG}$ of all off-measuring channels at "*i*" on-channel compared to the expression (8) decreases in $Z_{iek}\,/\,Z_{2jiS}$ times. For above-given conditions, adopting AEC becomes negligible mainly.

Analysis of (9) envisages that both AEC and MEC input circuit of IA significantly affect the measurement accuracy in working conditions. In order to raise it, the manual zeroing and conversion factor IA specification apply. However, while operating the values of both factors vary substantially, worsening MCMI accuracy.

4.3 Error Correction of Multi-Channel Measuring Instruments

Analysis ratio of (1) to (9) helps to identify the AEC significant affect the MCMI metrological properties in working conditions. For their adjustment, manual MCMI zeroing applies [15].

Usually CPS MCMIs are considered as distributed systems, measurable objects of which are located at appreciable distance from each other. So, suppose that it is almost impossible to carry out instrument's zeroing of every measuring channel at manual mode. To automate the MCMI error adjusting process it seems to be better the inverting switching input of gauging signals; input polarity switch would be located as close as possible to sensor output [14, 16]. If applicable IA, this switch should be near-by the input amplifier (Fig. 4).

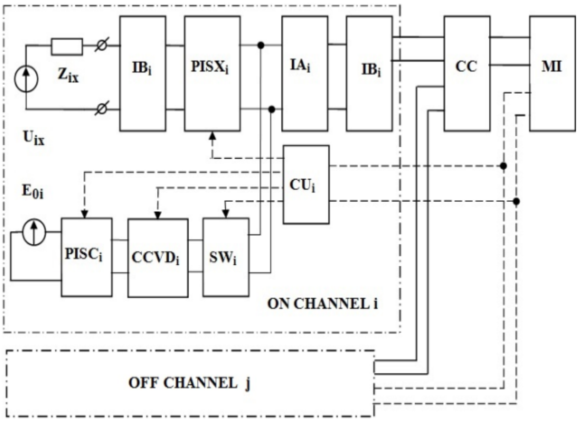

Fig. 4. Multi-channel measuring instruments with remote errors correction: PISX, PISC is the polarity inverse switch of measuring and calibration values accordingly; CU is the control unit; CCVD is the code-control voltage divider; SW is the switch.

In working conditions, MEC MCMI is characterized by significant dispersion (up to ± 2 %). Therefore, the problems in application emerge. We propose to perform the MCMI remote calibration basing on the code-control voltage measure (further CCVM) located in every measuring channel. It can be realize due to availability of modern microelectronics. During calibrating the output signal of CCVM $U_{ik}=kE_{0i}$ feed the measuring channel input, so the sensor measuring output signal U_{ix} is disconnected. The available set of calibration codes is transmitted to the CCVM from CNT MSMI. Output voltage of CCVM is converted in calibration result code N_{ik}, where i is the number of channel; k takes the values 1, 2, ..., K (K is the maximum number of calibration codes meanings).

While i on-channel has to be calibrated, it sends the N_{ik} code:

$$N_{ik}=0.5\left(N_{1ik}-N_{2ik}\right)= \\ =0.5k_{iA}k_{ADC}\left(U_{ik}+\Delta_{iAc}\right), \tag{11}$$

where N_{1ik}, N_{2ik} is the measurement results codes of the calibration voltage $U_{ik}=kE_{0i}$ for direct and reverse polarity of PISC connection, E_{0i} is the reference voltage, k_{ADC} is the ADC conversion factor, $\Delta_{IAc}=0.5[(I_{iA}+I_{iPC})\Delta Z_{iPC}+\Delta I_{iPC}Z_{iPC}]$ is the uncorrected value AEC, I_{iPC}, ΔI_{iPC} is the average value and absolute dispersion of reverse currents keys PISCi respectively, Z_{iPC}, ΔZ_{iPC} is the average value resistance and resistance match between channels “on” keys PISCi accordingly.

During the measurement of i on-channel, the sensor signal U_{ix} is received with the measurement result code N_{ix}:

$$N_{ix}=0.5\left(N_{1ix}-N_{2ix}\right)= \\ =0.5k_{iA}k_{ADC}\left(U_{ix}+\Delta_{iAx}\right), \tag{12}$$

where N_{1ix}, N_{2ix} is the measurement results codes of sensor output U_{ix} signal for direct and reverse polarity of PISXi connection, $\Delta_{IAx}=0.5[(I_{iA}+I_{iPX})\Delta Z_{iPX}+\Delta I_{iPX}Z_{iXX}]$ is the uncorrected AEC value, I_{iPX}, ΔI_{iPX} is the average value and absolute dispersion of reverse currents keys PISXi respectively, $\Delta Z_{iPX}=Z_{iX}+Z_{1iB}+Z_{iPX}$, Z_{iPX}, ΔZ_{iPX} is the average value resistance and resistance match between on-keys PISXi respectively.

The determined value is transformed in:

$$N_{ix}=N_{1ik}\frac{U_{ix}+\Delta_{IAx}}{U_{ik}+\Delta_{IAc}}=N_{1ik}\frac{U_{ix}}{U_{ik}}\left(1+\frac{\Delta_{IAx}-\Delta_{IAc}}{U_{ik}}\right) \tag{13}$$

MCMI MEC depends on performance of the reference voltage E_{0i} and on the CCVD conversion coefficient k. For the estimation of uncorrected errors limit we take the ordinary values for ADG787 switch [17] (I_{iA} =30 nA max, $I_{iPX}\simeq I_{iPK}\simeq$20 nA max, $Z_{iPX}\simeq Z_{iPK}\simeq$ 3.35 Ohm max, $\Delta Z_{iPX,C}\simeq$0.1 Ohm), $Z_{iX}+Z_{1IB}\le$1 $kOhm$ max, $\Delta I_{iPX}\simeq\Delta I_{iPC}\simeq$0.05 $I_{iPC}\simeq$ $\simeq 5\cdot10^{-2}\cdot2\cdot10^{-8}=1$ nA, then $\Delta_{IAc}\simeq$4 nV, $\Delta_{IAx}\simeq$0.1 μV. By performed while calibrating procedure the AEC uncorrected values become negligible for practical requirements. Then remains the unadjusted AEC, and its value is determined during the measurement by the total resistances of the sensor and IB, and also by the reverse currents differences of on-keys PISX and PISC. Studies envisaged that this difference does not exceed several per cent for modern MOS chips. So, it can be realized accurate MCMIs.

To insure high accuracy in working conditions, we propose method of remote calibration. It should be measured the actual output voltage U_{ik} for k different factors of division in every measuring channel at training stage of MCMI (on the step of adjustment). All K values of output voltages U_{iK} are measured by accurate voltmeter for every of k division factor getting the codes array N_{uik}. Then the same voltage values U_{ik} are measured by MCMI and received other codes N_{ik}. In MCMI memory the high-mentioned array N_{uik} by known method is entered and the appropriate calibration coefficients $K_{ik}=N_{ik}/N_{uik}$ is computed. They are fixed in MCMI memory and further apply at determination of the measurement result code N_{ix}:

$$N_{ix}=K_{iK}U_{ix} \tag{14}$$

Reference voltage values $U_{iK}=kE_{oi}$ of CCVD vary during work. To reduce the impact of these changes, must be selected the stable electronic components, for example, with parameters of reference voltage $\partial E_{io}/\partial\theta \le \pm 2\cdot 10^{-6}\ 1/K$ and CCVD $\partial k_i/\partial\theta \le \pm 2\cdot 10^{-6}\ 1/K$ in the temperature range -25...+85 °C [18-19]. Then changing values $U_{iк}$ and therefore $К_{iк}$ would not exceed ±0.026 %. This range of variation is satisfactory for measurements. The high temperature stability of suggested CCVM structure and the individual calibration possibility while debugging make it possible to obtain reference voltages within wide range, from a few millivolts to nearly reference voltage.

The same feature can apply to verify the MCMI metrological properties directly on-site by the portable CCVM. During adjusting it should be accurately gauged the k output measures $U_{iк}$ for every measuring channel. As regulations require, these points have to be arrange evenly along the measuring range. Value that is close to the maximum measuring range, can be used as a working standard at i on-measuring channel. MCMI on-site verification by means of CCVM excluding measuring sensors, assures the particular possibility of metrological checking of all channels. Portable CCVM is protected against varying operation conditions by implying the protective and preventive methods. Obviously, it needs to develop appropriate software for the prompted method implementation.

4.4. Experimental Investigations of Code Control Voltage Measure

A number of MCMIs has been implemented before, and their metrological maintenance is not sufficiently correct. Indeed, for quick calibration already active MCMIs the market offers several types of portable calibrators. Their main drawbacks are complexity and necessity of calibration results correction caused by possible changes of working conditions. Simultaneously calibrators drift themselves, and there emerge the contact EMFs in connection points to MCMI. To avoid them, we suggest the voltage calibrator (further VC) with error self-correction (Fig. 5).

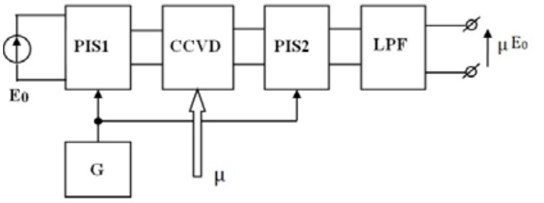

Fig. 5. Scheme of portable code control measure with automatic errors correction: PIS1, PIS2 is the first and the second polarity inverse switch, LPF is the low pass filter, G is the correction frequency generator, μ is the control code of CCVD.

In working conditions, calibrator requires the periodic manual AEC adjustment, which prolongs duration and complexity of metrological works. In such way, we propose to provide the AEC automatic correction.

The foundation of AEC automatic adjustment bases on two synchronous polarity switches operation that are located at the input and output of calibrator PIS1 and PIS2 respectively. The output voltage VC averaging follows this step.

The averaging can be carried out both in digital form and in analogue form when using LPF. Then the digital processing of results is the sum of even number of output signals VC conversions. For PIS1 and PIS2 one polarity of calibrator output voltage U_{k1i} we receive:

$$U_{k1i} = \mu_{iH}\left[E_{0H} + e_1\right]\left(1 + \delta_{\mu\, i} + \delta_E\right) + e_2\,, \qquad (15)$$

while for the other polarity is defined U_{k2i}:

$$U_{k2i} = \mu_{iH}\left[E_{0H} - e_1\right]\left(1 + \delta_{\mu\, i} + \delta_E\right) - e_2\,, \qquad (16)$$

where μ_{iH} is the nominal code of CCVD (DAC), E_{0H} is the nominal value of reference voltage, $\delta_{\mu i}$, δ_E is the relative error of CCVD and reference voltage respectively; e_1, e_2 is the AEC buffers of input and output voltages respectively.

At averaging, the output voltage value U_{ki} of calibrator for the current code μ_i, is determined as:

$$U_{ki} = 0{,}5\left(U_{k1i} + U_{k2i}\right) = 0{,}5\mu_{iH}E_{0H}\left(1 + \delta_{\mu\, i} + \delta_E\right) \qquad (17)$$

Results of modelling of designed scheme coincided with experimental results. In experiments, for calibrator was selected reference voltage with output voltage E_0=100 mV, and DAC codes change from 0 to 1 in increments of 0.25. To test the AEC impact on the obtained results we have been submitted e_1, e_2 = 15 mV from the stable power supply. It was received two sets of experimental results: output CCVM voltage without AEC, U_{K1}, mV and the output CCVM voltage with AEC source, U_{K2}, mV (Table 1).

Table 1. Investigation results of code control voltage measure experimental unit.

No.	μ_H	U_{K1}, (mV)	U_{K2}, (mV)
1.	0	-0.003	-0.003
2.	0.25	25.007	25.007
3.	0.5	50.015	50.014
4.	0.75	75.023	75.022
5.	1	100.031	100.031

The AEC imitator values are selected a priori more the possible values of equivalent offset voltage amplifiers, which use in the calibrator scheme. Simulator equivalent voltage AEC housed in various characteristic points layout VC, namely the inputs, outputs and all feedback loops of operational amplifiers. Discrete resistor voltage divider is used. The CCVM output voltage is measured by multimeter Picotest M3511A, which has those technical parameters as measurement range DCV 100 mV, accuracy 0.012 % in 1 year, least significant digit at average 1 μV.

If the experiment results analysis shows, that numeric data at the third and the forth columns Table 1 not differ by more than one least significant digit of using voltmeter (±1 μV). This confirms the theoretical assumptions for the possibilities of remote automatic calibration of measuring channels MCMI CFS.

5. Conclusions

1) Basic error factors of multi-channel measuring instruments due to equivalent input voltages and currents shifts, the influence of the switch channels, connecting lines, non-informative parameters of sources of measuring signals, common mode voltages, measured voltage penetration of other disconnected channels are considered. It is shown that the errors inherent in multi-channel measuring instruments with isolated channels can significantly exceed the similar ones of traditional structures.

2) Remote adjustment errors for developed multi-channel measuring instruments of CFS are suggested to carry out by means of embedded code-control voltage measures. For both multichannel measuring instruments and embedded code-control voltage measures, the additive error components correction is proposed to perform by inverted switching implementation. For multiplicative error component correction is suggested to implement code-control voltage measures based on stable voltage reference source and DAC multiplier.

3) For on-line errors correction of multichannel measuring instruments, the portable and compact code-control voltage measures with implementation of the input signal double inverting method are suggested. As result, the obtained additive error value does not exceed ±1 μV ensuring the high accuracy and stability of mentioned instruments for CPS operation.

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References

[1]. ISO 10012:2003. Measurement management systems – Requirements for measurement process and measuring equipment.

[2]. Smart Sensor Systems, edited by G. Mejer, *John Wiley & Sons, Ltd*, 2008.

[3]. J. W. Gardner, V. K. Varadan, O. O. Awadelkarim, Microsensors, MEMS, and Smart Devices, *John Wiley & Sons Ltd,* Chichester, England, 2001.

[4]. ATEX directive 2014/34/EU, Decision No. 768/2008/EC of the EPC of 9 July 2008 on a common framework for the marketing of products, Brussels, 21.11.2011 under reference COM (2011) 763 final.

[5]. Explosion protection. Theory and practice. PHOENIX CONTACT GmbH & Co. KG, Web Portal (http://www.phoenixcontact.com).

[6]. C. Lehrmann, D. Seehase, M. Sattler, M. Gruner, Latest news on explosion protection, Ex-Manual, *VEM*, 2013.

[7]. Data Acquisition Handbook, A Reference for DAQ and Analog & Digital Signal Conditioning, 3rd Ed., *Measurement Computing Corporation,* 2012.

[8]. Scott Wayne, Finding the Needle in a Haystack: Measuring small differential voltages in the presence of large common-mode voltages, *Analog Dialogue,* 34, 1, 2000, pp. 1-4, (http://www.analog.com//)

[9]. Instrumentation and Measurement, *Analog Devices Inc.,* 2015, (http://www.analog.com/en/applications/markets/instrumentation-and-measurement.html).

[10]. Data Acquisition Systems, *Omega Company Products*, One Omega Drive, Stamford, CT 06907, 1-888-TC-OMEGA USA, (http://www.omega.com/techref/pdf/dasintro.pdf).

[11]. Data Acquisition (DAQ) Fundamentals, Application Note 007, *National Instruments Corp.,* August 1999: (http://physweb.bgu.ac.il/COURSES/SignalNoise/data_aquisition_fundamental.pdf).

[12]. Data Acquisition, *Cole-Parmer Instrument Company*, 2015, (http://www.coleparmer.com/Category/Data_Acquisition/741).

[13]. Fluke Multifunction Calibration Tools, *Fluke Inc.,* 2015. (http://en-us.fluke.com/products/multifunction-calibrators/)

[14]. V. Yatsuk, P. Malachivsky, Methods of Increase of Measurement Accuracy, *Beskyd-bit edition*, Lviv, 2008 (in Ukrainian).

[15]. Precision, Wide Bandwidth 3-Port Isolation Amplifier AD 210, *Analog Devices Inc*., Web Portal (http://www.analog.com/media/en/technical-documentation/data-sheets/AD210.pdf).

[16]. Yatsuk V., Stolyarchuk P., Mikhaleva M., Barylo G., Intelligent Data Acquisition System Error Correction in Working External Conditions, in *Proceedings of the 3rd IEEE Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS'05)*, Sofia, Bulgaria, September 5-7, 2005, pp. 51-54.

[17]. 2.5 Ω CMOS Low Power Dual 2:1 Mux/Demux USB 1.1 Switch ADG787, *Analog Devices Inc*., Web Portal (http://www.analog.com/media/en/technical-documentation/data-sheets/ADG787.pdf).

[18]. Datasheet Catalog.com Web Portal (http://www.datasheet catalog.com/).

[19]. Catalog ELFA DISTRELEC Web Portal (http://www.online-electronics.com.ua/catalog/).