DIGITAL METER FOR THE TEMPERATURE OF MELTED METALS

N. I. Gribok, V. I. Zorii,
S. A. Savenko, Yu. V. Sasin,
and V. V. Osinchuk

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Measurement of the temperature of melted metals in furnaces with electrical contact, electric arc, and induction heating is accompanied by the significant influence of influencing factors $\vec{\xi}$ external to the measurement facility (MF) (the ambient temperature, the dustiness of the room, interference of a general kind with nonsymmetry of the fluctuations relative to the time axis, etc.) on the result N_1 of analog–digital conversion of the output thermal emf E_X of the thermoelectric converter (TC)

$$N_1=a_0[\vec{\xi},\vec{Q},\vec{\eta}_x]+a_1[\vec{\xi},\vec{Q},\vec{\eta}_x]=\bar{a}_{01}+\mathring{a}_{01}+[a_{1n}+\bar{a}_{11}+\mathring{a}_{11}]E_x, \tag{1}$$

where

$$a_0[\cdot]=a_0[\vec{\xi},\vec{Q},\vec{\eta}_x]=\bar{a}_{01}+\mathring{a}_{01};$$

$$a_1[\cdot]=a_1[\vec{\xi},\vec{Q},\vec{\eta}_x]=a_{1n}+\bar{a}_{11}+\mathring{a}_{11}$$

are, respectively, the additive and multiplicative components of the transformation function of the measuring loop, a_{1n} is the nominal value of the coefficient $a_1[\cdot]$, $\bar{a}_{01}$, $\bar{a}_{11}$ and $\mathring{a}_{01}$, $\mathring{a}_{11}$ are the systematic and centering components of the random errors in the coefficients $a_0[\cdot]$ and $a_1[\cdot]$, $\vec{Q}$ is the vector of the MF structural parameters, and $\vec{\eta}_X$ is the vector of the noninformative parameters of the thermal converter.

That $a_0[\cdot]$ is not equal to zero for a low output signal level of the thermal converter results in a significant increase in the measurement error. Application of manual calibration to diminish $a_0[\cdot]$ during execution of the measurements under industrial production conditions is impossible in a number of cases and hardly effective for nonsymmetry of the interference voltage with respect to the time axis since an uncorrected component

$$a_0[\vec{\xi},\vec{Q},\vec{\eta}_x]-a_0[\vec{\xi},\vec{Q}]$$

remains here in the absence of a priori information about the value of $\vec{\eta}_X$.

To automate the calibration process a second transformation cycle was introduced in [1] to obtain the reading

$$N_2=a_0[\vec{\xi},\vec{Q}]=\bar{a}_{02}+\mathring{a}_{02} \tag{2}$$

for E_X-o and the thermal emf value is determined from

$$E_x^*=\frac{N_1-N_2}{a_{1n}}=\frac{(\bar{a}_{01}-\bar{a}_{02})+(\mathring{a}_{01}-\mathring{a}_{02})+(\bar{a}_{11}+\mathring{a}_{11})E_x}{a_{1n}}+E_x,$$

where E_X^* is the measured value to E_X.

The variance of the measurement error is found from the expression

$$\begin{aligned}D_{E_x^*}=M[(E_x^*-E_x)^2]=\frac{1}{a_{1n}^2}[&D_{\bar{a}_{01}}-2K_{\bar{a}_{01}\bar{a}_{02}}-D_{\bar{a}_{02}}+\\&+2(K_{\bar{a}_{01}\mathring{a}_{01}}-K_{\bar{a}_{02}\mathring{a}_{01}}-K_{\bar{a}_{01}\mathring{a}_{02}}-K_{\bar{a}_{02}\mathring{a}_{02}})+D_{\mathring{a}_{01}}-\\&-2K_{\mathring{a}_{01}\mathring{a}_{02}}+D_{\mathring{a}_{02}}+2E_x(K_{\bar{a}_{11}\bar{a}_{01}}+K_{\mathring{a}_{11}\bar{a}_{01}}-K_{\bar{a}_{11}\bar{a}_{02}}-\\&-K_{\mathring{a}_{11}\bar{a}_{02}}+K_{\bar{a}_{11}\mathring{a}_{01}}+K_{\mathring{a}_{11}\mathring{a}_{01}}-K_{\bar{a}_{11}\mathring{a}_{02}}-K_{\mathring{a}_{11}\mathring{a}_{02}})+E_x^2(D_{\bar{a}_{11}}+2K_{\bar{a}_{11}\mathring{a}_{11}}+D_{\mathring{a}_{11}})],\end{aligned} \tag{3}$$

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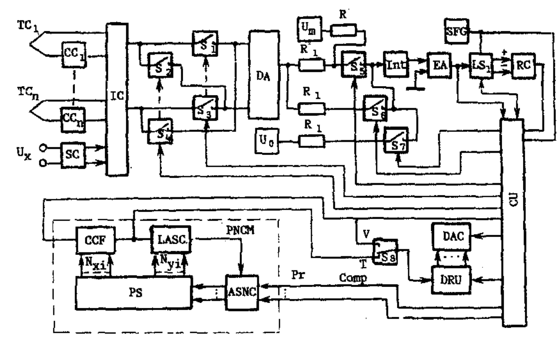

Fig. 1

TABLE 1

Kind of TC used		Measurement range, °C	Resolution, °C
ВР 5/20$_{68}$—1,	A—1	0—1800	1
ВР 5/20$_{68}$—2,	A—2	0—1800	1
ВР 5/20$_{68}$—3,	A—3	0—1800	1
ПП$_{68}$,	S	0—1600	1
ХА$_{68}$,	K	0—1300	1
ХК$_{68}$,	L	0—800	0,1; 1
ПР$_{68}$,	B	0—1800	1

where K(·) are the correlation functions of the quantities indicated by the subscripts in (3).

In the absence of correlation between the systematic $\bar{a}_{01}$, $\bar{a}_{02}$, $\bar{a}_{11}$, $\bar{a}_{12}$ and centered $\mathring{a}_{01}$, $\mathring{a}_{02}$, $\mathring{a}_{11}$, $\mathring{a}_{12}$ components in (1) and (2) the expression (3) simplifies

$$D_{E_x^*}=\frac{1}{a_{1n}^2}[D_{\bar{a}_{01}}+D_{\bar{a}_{02}}-2K_{\bar{a}_{01}\bar{a}_{02}}+D_{\mathring{a}_{01}}-2K_{\mathring{a}_{01}\mathring{a}_{02}}+D_{\mathring{a}_{02}}+E_x^2(D_{\bar{a}_{11}}+D_{\mathring{a}_{11}})]. \tag{4}$$

It is seen from (1), (2), (4) that even by selecting a significant fast-response of the measurements as compared with the time changes $a_0[\cdot]$, $a_1[\cdot]$, the additive component is not corrected completely because of $\vec{\eta}_x=0$ in (2). Consequently, none of the serially manufactured domestic voltmeters with double integration assures high interference-immunity of the measurements relative to the interference with nonsymmetry of the fluctuations relative to the time axis [2].

A method of commutative inversion is realized in [3] when measuring the temperature by using a TC. Starting from the system of equations

$$\left.\begin{aligned} N_1 &= (\bar{a}_{01}+\mathring{a}_{01})+(a_{1n}+\bar{a}_{11}+\mathring{a}_{11})E_x; \\ N_2 &= (\bar{a}_{02}+\mathring{a}_{02})+(a_{1n}+\bar{a}_{12}+\mathring{a}_{12})-(E_x), \end{aligned}\right\} \tag{5}$$

the value of E_x is determined from the expression

$$E_x^*=\frac{N_1-N_2}{2a_{1n}}=\frac{(\bar{a}_{01}-\bar{a}_{02})+(\mathring{a}_{01}-\mathring{a}_{02})+[(\bar{a}_{11}+\bar{a}_{12})+(\mathring{a}_{11}+\mathring{a}_{12})]E_x}{2a_{1n}}+E_x$$

Analogously to (3) and (4) we find the variance of the measurement error

$$D_{E_x^*}=\frac{1}{4a_{1n}^2}[D_{\bar{a}_{01}}-2K_{\bar{a}_{01}\bar{a}_{02}}+D_{\bar{a}_{02}}+D_{\mathring{a}_{01}}-2K_{\mathring{a}_{01}\mathring{a}_{02}}+E_x^2(D_{\bar{a}_{11}}+2K_{\bar{a}_{11}\bar{a}_{12}}+D_{\bar{a}_{12}}+D_{\mathring{a}_{11}}+2K_{\mathring{a}_{11}\mathring{a}_{12}}+D_{\mathring{a}_{12}})].$$

Since

$$D_{\bar{a}_{11}}=D_{\bar{a}_{12}}=D_{\bar{a}_{1}};\quad K_{\bar{a}_{01}\bar{a}_{02}}=D_{\bar{a}_{0}}=D_{\bar{a}_{01}}=D_{\bar{a}_{02}}$$

$$\text{for } \vec{\eta}_x=\text{const}$$

can be assured by selection of the measurement fast-response in two measurement cycles, then the error due to $\mathring{a}_{01}$, $\mathring{a}_{02}$, $\mathring{a}_{11}$, $\bar{a}_{11}$, $\bar{a}_{12}$, $\mathring{a}_{12}$ not being equal to zero will be predominant. A further diminution of the random measurement facilities with two-cycle integration during static averaging of the intermediate conversion results.

The positive properties of the algorithm (5) are determined by selecting the scheme to measure the thermal emf E_x (see Fig. 1) corresponding to the temperature θ_x being measured by using a TC (the influence of the temperature of the free TC ends is eliminated by introducing parametric correction apparatus with two thermal resistors [4]). The thermal emf E_x is magnified by the differential amplifier DA to a normalized level and is converted by the voltage converter into a time interval by using weighted integration. The control unit CU closes the switches S_1, S_3 in the first measurement cycle. The voltage at the DA output equals $U_1(t) = K[E_x + U_i(t)] + U_{ad}$, where $U_i(t)$ is the inferference voltage and U_{ad} is the signal additive component at the DA output.

The switch S_5 is closed in the time $T_1 = 3T/2$ by the CU signal, while the switch S_6 is closed in the time $T/2$ from the time $T/2$ to the time T of the 50-Hz grid voltage. To obtain a unipolar reading, a mixing voltage U_m is delivered to the input of the switch S_5 through the resistance R. During two-cycle conversion of the voltage U_1

$$\int_0^{3T/2}\left[\frac{K(E_x+U_i(t))}{R_1C}+\frac{U_m}{R}+U_{ad}\right]dt+\int_{T/2}^{T}\left[\frac{K[E_x+U_i(t)]+U_{ad}}{R_1C/2}\right]dt+\int_{3T/2}^{t_1}\frac{U_0}{R_1C}dt=U_c$$

a number of pulses

$$N_1=f_0\left(t_1-\frac{3T}{2}\right)=\frac{f_0}{U_0}\left[U_a-\frac{3TU_m}{R_1C}\int_0^{3T/2}\frac{KU_i(t)}{R_1C}dt-\int_{T/2}^{T}\frac{2KU_i(t)}{R_1C}dt-\frac{2KT}{R_1C}E_x\right]$$

proceeds to the summing input of the reversive counter RC from the selector LS output, where U_a is the activation threshold of the equalizing apparatus EA.

The switches S_2, S_4 are closed by the signal from the CU output in the second measurement cycle, while the switches S_1, S_3 are opened. The DA output voltage $U_2(t) = K[-E_x + U_i(t)] + U_{ad}$ is converted by two-cycle integration analogously to that described above into the number of pulses

$$N_2=f_0\left(t_2-\frac{3T}{2}\right)=\frac{f_0}{U_0}\left[U_a-\frac{3TU_m}{2R_1C}-\frac{2TU_{ad}}{R_1C}-\int_0^{3T/2}\frac{KU_i(t)}{R_1C}dt-\int_{T/2}^{T}\frac{2KU_i(t)}{R_1C}dt+\frac{2KT}{R_1C}E_x\right],$$

coming from the LS output to the subtracting input of the RC. A code of numbers

$$N=N_1-N_2=-\frac{4KTf_0}{R_1CU_0}E_x,$$

independent of the values of the parameters U_a, U_m, R, U_{ad}, $U_i(t)$ of the measuring loop, is fixed in the RC up to the time t_2. If the RC did not go over into the zeroth state up to the time t_2, then the CU develops a signal indicating the positive polarity of E_x since $N_1 > N_2$. In the opposite case, the thermal emf E_x will have negative polarity for $N_1 < N_2$. From the time t_2 pulses of a number N here proceed directly to the parametric nonlinearity correction module PNCM. For $E_x > 0$ the LS is open from the time t_2 and the pulses of frequency f_0 from the standard frequency generator SFG proceed to the RC input up to the time it goes over into the zeroth state.

When measuring a dc voltage the switch of the kind of operation S_8 is in the position "V" and the number of pulses N goes directly to the digital reading unit DRU. For $\frac{4KT}{R_1CU_0}=10^n$ the result of the measurement is proportional to the value of the voltage U_x being measured. The scale conversion of U_x is realized by using the scale converter SC.

To obtain a linear reading when measuring the temperature in a voltmeter circuit, functional converters for parametric correction of the nonlinearity of the TC conversion function should be introduced. One of the parameters in (6) should here be altered. Taking account of the significant inertia of the DA and the reduction of the interference-immunity during functional conversion of K, T_1, R_1 in the first integration cycle [5], it is expedient to change the parameters U_0, R_1 and f_0 functionally in the second integration cycle. The first two parameters can be altered by inserting functional converters into the analog portion of the apparatus [6], however, this can result in a reduction in the interference-immunity of the measurements. Consequently, in the meter under consideration parametric correction of the nonlinearity is applied in the digital portion of the apparatus.

The parametric nonlinearity correction module contains a code converter into frequency CCF, a long approximation section counter LASC, an approximation section number counter ASNC, and a permanent storage PS.

During correction of the nonlinearity, the code of numbers N goes to the CCF input with pulse repetition rate f_0 from the RFG reference frequency generator. The pulse frequency at the CCF output in the i-th approximation section is $f_i=\frac{f_0 N_{xi}}{N_0}$, where N_0 is the CCF constant, N_X is the code of numbers going from the PS output in the i-th section to the CCF input. A code of numbers N_{yi} equal to the duration of the approximation section here goes to the LASC input. With the termination of the i-th section the pulse from the LASC output transfers the ASNC into the (i+1)-th state. Codes of the numbers $N_{x(i+1)}$ and $N_{y(i+1)}$ here go from the PS output to the CCF and LASC inputs. The values of N_{xi} and N_{yi} are determined as follows. Let there be i approximation sections for a given TC calibration characteristic $E(\theta_X, 0)$, on each of which the approximation error does not exceed a given value γ_{max}. On the i-th approximation section the thermal emf E_X can be represented as

$$E_x=\Delta E_{x1}+\Delta E_{x2}+\ldots+\Delta E_{x(i-1)}+\Delta E_x, \tag{7}$$

where $\Delta E_{X1}=E_{X1}$; $\Delta E_{X2}=E_{X2}-E_{X1}$; ... ; $\Delta E_{X(i-1)}=E_{X(i-1)}-E_{X(i-2)}$; $\Delta E_X=E_X-E_{X(i-1)}$; $E_{X1}, \ldots, E_{X(i-1)}$ are values of the thermal emf at the beginning and ending points of the approximation sections.

Substituting (7) into (6), we have

$$N_1-N_2=-\frac{4KTf_0}{R_1CU_0}(\Delta E_{x1}+\Delta E_{x2}+\Delta E_{x3}+\ldots+\Delta E_{x(i-1)}+\Delta E_x).$$

The nonlinear dependence $E(\theta_X, 0)$ is replaced on each of the approximation sections by a straight line segment with slope $\Delta\theta_{Xi}/\Delta E_{Xi}$, which should numerically equal N_{Xi}/N_0 to obtain the code of numbers directly proportional to θ_X. Since $N_0=\text{const}$ for the CCF and ΔE_{Xi} and $\Delta\theta_{Xi}$ are determined on the basis of computing the nodes of a piecewise-linear approximation of the calibration characteristics of specific TC, then for each of the approximation sections $N_{Xi}=(\Delta\theta_{Xi}/\Delta E_{Xi})N_0$; $N_{yi}=\Delta\theta_{Xi}$. Consequently, when N pulses arrive at the CCR input from its output through the switch S_8, the number of pulses at the DRU input

$$N_{\theta x}=-\frac{4KTf_0}{R_1CU_0}\left[\frac{N_{x1}}{N_0}\Delta E_{x1}+\frac{N_{x2}}{N_0}\Delta E_{x2}+\ldots+\frac{N_{xi}}{N_0}\Delta(E_x-E_{x(i-1)})\right]$$

is proportional to the value of the temperature θ_X being measured.

Upon going over from one type of TC in another input commutator IC the appropriate TC_i (i=1, ..., n) with the compensation circuit CC_i is connected to the input of the switches $S_1, \ldots, S_4$. By using the CU the code of numbers that is the number of the initial approximation section for the TC_i is inscribed in the ASNC. This would afford the possibility of realizing a nonlinearity correction in a PS with 256 word capacity (K556PT4) for TC with a number 16 approximation section, for 16 kinds of thermal converters without increasing the apparatus expenditure.

The apparatus has the following technical characteristics: the voltage measurement limits are 10 mV, 100 mV, 1 V, 10 V, 100 V with representation of the measurement results by five decimal places; the main voltage measurement error is $\delta U=0.1+0.05(U_f/U_X-1)$, where U_f is the final value of the measurement range, U_X is the value of the voltage being measured, the fast response is 6 changes per second; attenuation of the interference of the normal kind of supply grid frequency is not less than 60 dB, attenuation of interference of a general kind of supply grid frequency is not less than 120 dB, and the time of unadjusted operation is not less than 2000 h.

The fundamental referred temperature error does not exceed 0.2% without taking account of the TC error. The technical characteristics of the apparatus are represented in the table.

The apparatus is equipped with the thermal converters TVR 301-1, TVR 301-2, TVR 301-3 which are placed on a portable pedestal together with a portable information panel and connected to the thermometer by using a flexible cable. Such a construction permits operational measurement of the temperature at different stages of the technological process and simultaneous storage of the measurement results. An audible signal in the portable panel denotes termination of the measurements. Extraction of the measurement results is executed in a decimal code on a digital panel, in a binary-decimal code 1-2-4-8 for recording on digital printers and in the form of a voltage from the output of the DAC digital–analog converter for recording on analog recorders.

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