Запропоновано вдосконалення переносного обладнання для контролювання каналів вимірювання напруги постійного струму кібер-фізичних систем на місці експлуатації. Адитивні зміщення та дрейфи вносять домінуючий вклад в похибку переносних калібраторів напруги постійного струму. Автоматичне коригування на основі методу подвійного комутаційного інвертування дає можливість підвищення продуктивності обслуговування системних вимірювачів напруги багатоканальних на місці експлуатації. Показано, що адитивні зміщення під час відтворення напруги постійного струму окрім еквівалентних напруг зміщення операційних підсилювачів, АЦП або ЦАП, обумовлені завадами спільного виду та струмами витоку через ізоляцію блоків живлення.

В розробленій структурі калібратора напруги постійного струму запропоновано використовувати метод подвійного комутаційного інвертування з подальшим аналоговим усередненням вихідного сигналу для автоматичного коригування адитивних зміщень. Проведений аналіз похибок та імітаційне моделювання показали принципову можливість коригування адитивних зміщень калібратора до значень, обмежених неідентичністю параметрів замкнених пар ключів.

Аналіз результатів експериментальних досліджень макету калібратора напруги показав інваріантність відтворюваних напруг від значення напруги та від місця розташування імітатора адитивної складової похибки в структурі макету.

Нескориговане значення похибки в режимі ручного керування не перевищувало ±1 мкВ для всіх відтворюваних значень вихідної напруги макету. Експериментально показано, що мінімальне значення нескоригованої похибки знаходиться на частоті комутації біля 1,2 кГц в межах ±5 мкВ. Розроблена схема може бути реалізована в базисі програмованих систем на чіпі, що суттєво покращує метрологічні характеристики, зменшує вартість реалізації і уніфікує переносні калібратори напруги та імітатори опору постійного струму

Ключові слова: переносний калібратор напруги, автоматичне коригування похибок, адитивне зміщення, калібрування приладів на місці експлуатації

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DEVELOPMENT OF PORTABLE DC VOLTAGE CALIBRATORS WITH ADDITIVE OFFSETS ADJUSTING

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1. Introduction

The ever-widespread introduction of cyber-physical systems (CPS), Internet of things (IoT) devices for industrial use and scattered measurement systems requires the development of fundamentally new approaches to metrological support [1]. Indeed, the classic methods of calibration, operational control, and metrological verification of the measuring channels (MC) of such devices in the laboratory conditions are meaningless, since they require dismantling of the whole dispersed system (Fig. 1). In addition to purely technical and organizational inconveniences and financial costs, verification of MC in, to a certain extent, «hothouse» conditions will not reflect most of their metrological features in real conditions of operation. In this case, no other parts of the measuring circle are checked (Fig. 1). In the case of testing individual measuring transducers, the operation of the modems, communication lines and central computer should be checked at the operation site [2].

Modern regulatory documents recommend the introduction of such measurement management systems that ensure the suitability of measuring equipment and measurement methods for intended use and the specified level of risk of obtaining unlikely measurand results [3]. Therefore, it is economically most expedient to carry out the metrological maintenance of MC CPS directly at the site of operation.

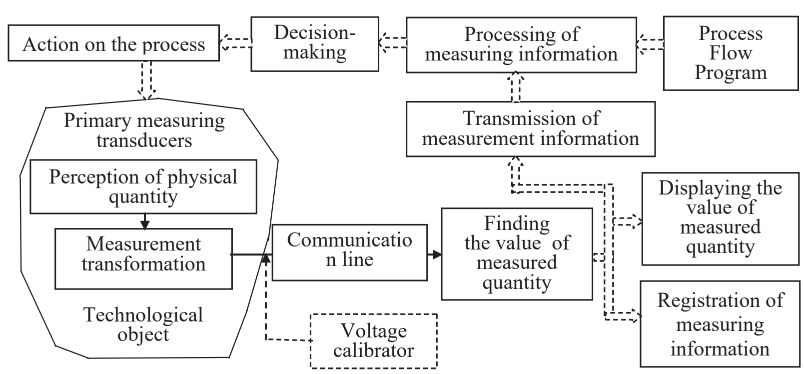

Fig. 1. Generalized block diagram of measuring channels of technological CPS

It is obvious that for the practical realization of this, calibrators of physical quantities with the possibility of placement directly in technological facilities are necessary. In most practical cases, this is either technically impossible, for example, nuclear power plants, or difficult and expensive because of the need to adjust the metrological characteristics of classical calibrators at the site of operation of the MC CPS. During operational control, the calibrator usually has several voltage values evenly distributed in the measurement range of the controlled means. In this case, at the point of operation of measuring instruments with low voltage inputs, for example, type S thermoelectric transducers, the additive offsets of the calibrator for all set values of codes should be corrected. This is due to the fact that the additive components of the errors of its input blocks are transformed into multiplicative ones. As a result, the service time becomes unreasonably large, and the procedure for operative control of the metrological state of MCs of measuring tools is significantly complicated. Therefore, the automation of the process of adjustment of the additive offsets eliminates the need for manual correction of the errors of direct current voltage calibrators and serves as a basis for a significant reduction of its mass and dimensional parameters [4, 5].

2. Literature review and problem statement

To increase the productivity of usage of metrological support tools at the site of operation of voltage and emf meters widely used in the industry, portable DC voltage calibrators (DCVC) [1, 2, 4] should be used. To reduce the offset voltage in conventional amplifiers, a transformation with modulation-demodulation with alternating signal switching in each half-period of the control signal is used. After demodulation, the offset voltage turns into a low-frequency noise and shifts it toward higher frequencies, but it can be reduced by the low-frequency filter. To improve the effectiveness of filtering, it is proposed to switch the signal after a period. This means that after the first one, two measurements with switches in the same position are performed every time. But through the parasitic capacitances during the switching of control signals and injecting of the switches channel charge, the residual offset voltage remains even after filtering and demodulation. A more fundamental solution of this problem is the use of a pair of additional switches, which operates at a much lower frequency than the main switches. External commutators are used to adjust the components of DC offsets in closed switches, generated during the signaling [1]. However, this method requires the usage of an additional low pass filter with a very small cutoff frequency. This filter can be easily applied as a digital one using the built-in microcontroller software. In general, MCs can be calibrated using hardware or software, or a combination of them. In portable devices, hardware calibration is typically used, for example, manual adjustment of the amplifiers offset. This leads to an increase in the complexity of debugging operations. Other types of calibrations are used in more sophisticated and more expensive means of measurement such as multi-channel metering information collection systems [2]. For calibration of the MC of dispersed CPS, it is advisable to use portable calibrators of electrical quantities. Taking into account the significant changes in environmental conditions at the site of operation, it is usually necessary to establish a zero level of the output voltage of the DCVC. These adjustments should be made at each change of the calibrator control code, since the additive offsets of some of its elements causes the multiplicative component of the error [4].

During the measurement of the low DC voltage, a number of methods have been developed for the automatic correction of the additive error component (AEC). However, during voltage reproduction due to the lack of automatic calibration methods, the output signals of the portable traditional DCVC are manually adjusted by the operator at the operating sites and represent a lengthy and laborious procedure [5]. In low-level signal processing systems, considerable attention should be paid to minimizing additive offsets both through equivalent offset voltages of the operational amplifiers, and as a result of common noise caused by the flow of currents through common buses. It should be analyzed in detail in each case, but the universal method of their reduction is periodic calibration, for example, by the operator at the operating sites [6]. The methods for reducing the effect of the operational amplifiers offset voltages are the use of certain types of internal or external calibration, such as conversion with modulation-demodulation, automatic adjustment, offset fitting or alternating current conversion. During the alternating current conversion, the frequency range of the signal is substantially limited, so it is not suitable for reproducing DC signals. Most operating amplifiers have certain capabilities to change their offset shape during the production process. For example, in the measuring amplifiers, the laser matching of resistors of the differential stage is used to balance the currents in each branch of the differential stage to reduce the offset voltage. However, after packing, the value of the offset voltage and its drift increases, usually to several hundreds of microvolts. Using transformation with modulation-demodulation or automatic error correction, it is possible to reduce the offset voltages to several tens of microvolts and their drift to several tens of nanovolts per °C [7]. For all of these methods, except for uncorrected errors in the given environmental conditions and at the present time, additive and multiplicative errors of the calibrators will increase due to changes in environmental conditions and over time.

Traditionally, DCVC represent a code-controlled divider CCVD of the reference voltage E_N with the initial scaling converter SC [5] (Fig. 2).

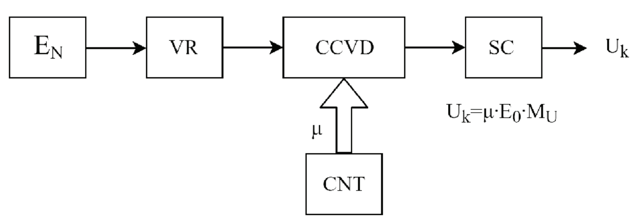

Fig. 2. Block diagram of DC voltage calibrators

The output voltage of the U_K classic DCVC will be given by the ratio:

$$U_K = U_{OT} = M\left[\mu\left(E_N+\Delta_{BF}\right)+\Delta_{CVD}\right]+\Delta_{OT}, \qquad (1)$$

where E_N is the output voltage of the source of the reference voltage; μ, M is the transmission factor, respectively, of the CCVD and SC; Δ_{BF}, Δ_{CCVD}, Δ_{OT} is the additive error component (AEC), respectively, of the voltage repeater VR, CCVD and SC.

Correction of the CCVD errors at the operating site is usually carried out manually by the operator adjusting its conversion function according to the built-in standards and it is labor-intensive and costly [2, 5–7]. In order to reduce the offset voltage of the operating amplifiers (OA), a number of technological methods are used – external tuning, laser tuning, electronic tuning and dynamic adjustment [8]. Laser devices are used to fit resistive materials in the input cascades on the chip of OA, manufactured by bipolar technology. After packing the chip into the body, the offset voltage of the OA, for example, INA826S type, increases to unacceptably large values of ±150 μV. In the process of electronic tuning, electronic resistors whose values are changed with the help of the built-in controller according to the OA output signal are embedded in the OA chip. This allows the values of the offset voltage of the enclosure OA, for example, OPA2191 type, up to ±25 μV. Dynamic adjustment due to switching emissions of switches makes it possible to reduce the offset voltage of the OA up to ±10 μV, which is too high for sensitive DC voltage meters. For the automation of the correction process in systems with variable transmission coefficient, a device is proposed in which the offset voltage values are digitized and stored [9]. The voltage of offset correction is inputted to the amplifier input circle using the DAC. In practice, this leads to the need of usage of sensitive and stable comparators and DACs, offset voltage and drift, which will determine the boundary metrological characteristics of the entire system. A similar circuitry is used to adjust the offset voltages of multi-stage broadband AC power amplifiers [10]. A method of adjusting the DC voltage offset in the analogue RF signal conversion channel consists in loosening the high frequency components using a high-pass filter (HPF), detecting the offset voltage, transforming it into a digital signal, and using the compensation module to convert into the anti-polar signal in such a way as to ensure reduction of the offset voltage to zero values [11]. However, the depth of adjustment of the offset voltage in such a device is low due the system inertia, caused by the time constant of the compensation module, which can also lead to the loss of the amplifier stability.

To construct precision DACs, the possibility of adjusting the multiplicative and additive components of error in the form of setting individual adjustments to the current value of control codes is proposed [12]. However, the value of these corrections should be determined by the calibration results of each model and entered and stored in the DAC memory. Such a method for correcting errors in the DCVC should be used during its implementation on the basis of programmable system-on-a-chip (PSoC), or design of a specialized intelligent microcircuit.

The equivalent offset voltage of a DC device can be corrected by the method of inputting a common negative feedback [7]. At the time of adjusting the offset voltage, the input signal must be switched off and an analogue correction signal is fed to the input of the device. The use of this method will be significantly influenced by their own AEC of negative feedback loops, as well as the parameters of the switching elements. The use of amplifiers with periodic offset voltage correction [7] will lead to an increase in the unadjusted AEC of the DCVC due to the residual stresses of the offset of the individual amplifiers and the cost increase of the practical implementation of the DCVC. There is no need to switch off the input voltage in amplifiers with modulation-demodulation (AMDM), the limiting capabilities of which are determined by a number of error sources [1, 5–7]. These are the penetration of the switching emissions of the signal switches to the output of the amplifier, the modulation error, the passage of the voltage of the modulation frequency due to the low efficiency of the LPF [5]. The indicated shortcomings of AMDM will lead to complications and rising cost of portable DCVC. Due to the need to use several LPF, the implementation of the DCVC in the basis of PSoC or in the form of an integrated circuit will be greatly complicated.

It is possible to significantly reduce the influence of AMDM error sources in amplifiers with dual modulation-demodulation (nested-chopper technique) [1]. Internal switches operate at a frequency significantly higher than the frequency of conjugation of white and $1/f$ noise (several tens of kilohertz), and external switches operate at a fairly low frequency (several tens of hertz). Thanks to such circuitry, it is possible to reduce the unadjusted offset voltage to the values of tenths of a microvolt [13]. However, during the implementation of the DCVC on such OA, no additive offsets due to the presence of common types of noise (common power wires), leakage currents through isolation, thermoelectric phenomena, electrostatic disturbances, etc. are corrected [14].

Modern integral technology makes it possible to correct various components of the error of the transforming systems with the introduction of hardware and software redundancy during implementation on one chip. Thus, we propose a new technology of the built-in self-calibration system of multi-bit rate fast-acting ADCs of bitwise equilibrium [15]. The proposed self-calibration scheme corrects the DAC errors by connecting auxiliary capacitors from an additional correction array in the calibration mode. In addition, in order to minimize the offset voltage of the comparator in the ADC, the voltage amplifier with auto-calibration is proposed [16]. However, for the correct use of such ADCs, it is necessary to carry out an external calibration procedure using precision equipment and memorize a large amount of information to determine and store the corrections to the set values of the DCVC code.

To correct the offset voltage of the OA, the switching inverting circuitry is used, which in the case of integral execution allows reducing the offset voltage to several tenths of a microvolt [17]. In the case of the introduction of additional OPs into the channel of periodic correction of the errors of the main channel, it is possible to reduce the offset voltage of serially produced OAs, for example, types AD8551/AD8552/AD8554, to several microvolts [18]. However, in the structure of the DCVC, in addition to the offset voltage of the OA, other sources of additive offsets, for example, contact thermoEMF, voltage drops on common wires between stages, leakage currents through isolation, etc. will also affect [14]. The smallest values of the unadjusted value of the OA offset voltage can be achieved in a structure with a digital adjustment [19]. This technology consists in adjusting the offset voltage of the OP circuit after manufacture by programming a digital weighted current source – DAC. This technique uses the mixed capabilities of the CMOS processor manufacturing process in conjunction with the digital correction technique using an additional OA with drift adjustment. Once the tuning is complete, the processing loop is blocked to prevent the possibility of accidental exposure of the end user [19]. The disadvantages include the effect of additive offsets of other blocks of DCVC [14].

In practice, high precision and sensitivity should be ensured when constructing portable DCVC for measuring metrological characteristics of measuring channels, for example, thermoelectric thermometers for working with platinum thermoelectric transducers PP (S). So the least significant digit should be no more than one microvolt, the limit of the permissible values of absolute error – about a few microvolts in the range of ambient temperatures from 0 to +50 °C. In addition, the structure of the voltage calibrator must be unified with code-controlled simulators of electric resistance and DC calibrators [5].

Therefore, the improvement of portable constant voltage calibrators on the basis of modern microelectronic and information technologies will facilitate its implementation as an integrated microcircuit and improve the metrological reliability of operational control of the characteristics of the entire measuring range at the site of operation.

3. The aim and objectives of the study

The aim of the study is to develop a structure of the DC voltage calibrator for the operational control of low voltage meters. This will increase the accuracy and simplify the procedure for operational control, verification and testing of measuring channels of DC voltage under operating conditions.

To achieve this aim, the following objectives are accomplished:

– to substantiate theoretically the choice of the method of automatic correction of additive offsets in the structures of DC voltage calibrators;

– to develop a method of automatic correction of the additive components of the error of the transformation path;

– to study the method of correction of the additive offsets of portable voltage calibrators taking into account the parameters of the element base;

– to conduct experimental research of the model of portable DC voltage calibrators.

4. Justification of the choice of the method of automatic additive offsets correction in voltage calibrators

An analysis of the ways to reduce the reproduction errors in low DC voltage calibrators showed that the method of setting the zero-level of the DCVC in manual mode at the site of operation was mainly used [1, 2]. Given the change in the output voltage of the DCVC in a wide range, such adjustments must be made during each change of the calibrator control code, since the AEC Δ_{BF} of the input buffer *BF* is converted into a multiplicative error component (MEC) ((1) and Fig. 2).

This complicates the technique and reduces the speed and practically makes it impossible to use such a calibrator on the objects under investigation, where the presence of the operator is not desirable, or impossible, for example, aggressive chemical production, nuclear power plants, etc. Using periodic drift correction amplifiers in DCVC complicates and raises the cost of their structure and does not eliminate the need for manual setting of zero level due to the presence of a number of other sources of additive offsets [14]. It is possible to eliminate the need to manually set the zero-level of the DCVC using several amplifiers (Fig. 2) with dual modulation-demodulation (nested-chopper technique). However, due to the need to use a long-term low-pass filter, the mass-dimensional parameters and the cost of the calibrator will increase significantly. In addition, this will complicate the possibility of implementing the DCVC in the PSoC basis.

Therefore, further analysis is aimed at developing the structure of the DCVC with the automatic adjustment of additive offsets, the boundary metrological properties of which are closer to the possibilities of using the technology of double modulation-demodulation and would be suitable for implementation in the integrated technology.

5. Description of the developed structure of voltage calibrator with automatic adjustment of additive offsets

The block diagram of the experimental setting for the reproduction of the DC voltage with the automatic adjustment of the additive offsets is shown in Fig. 3. It contains:

– two reference voltage sources E_{N1}, E_{N2} included between the power supply leads;

– power supply sources U_{S1}, U_{S2};

– input repeater IR;

– code-controlled voltage divider CCVD;

– input S_{11} and output S_{12} polarity switches;

– output repeater OR and voltage inverter VI;

– low-pass filter LPF;

– storage capacitor C for forming the output voltage of the DCVC.

The measuring scheme (Fig. 3) provides a number of measures to ensure noise immunity and stability of conversion [5]. The construction basis of the block diagram of the voltage calibrator with automatic adjustment of additive offsets is the principle of double modulation-demodulation with the use of two reference voltage sources (RVS). To automate the error correction process, it is expedient to use the method of dual switching inversion with the output averaging low-pass filter (LPF) [1].

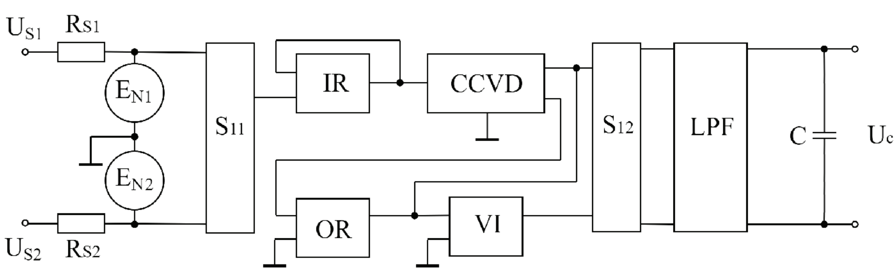

Fig. 3. Block diagram of the experimental setting for reproducing the DC voltage with the automatic adjustment of the additive offsets

The output calibrated voltage U_K is obtained as the algebraic sum of the voltages on the original storage capacitor $U_K=U_{K1}-U_{K2}$, where U_{K1}, U_{K2} are the output voltages on the capacitor C in various half-periods of the control frequency when connecting the RVS E_{N1} and E_{N2} of different polarities relative to the calibrator common bus. With the help of the input switch S_{11}, the inputs of the calibrator are switched alternately to both outputs of the RVS. The output switch S_{12} synchronously with the first one connects the output voltage OR and inverter VI to the storage capacitor C. The output voltage DA2 U_{K11} is given by the following expression:

$$U_{k11} = -\left(E_{N1} + e_1\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_2\right) + e_{211}, \qquad (2)$$

where E_{N1} is the value of the RVS output voltage; $\Delta_1 = 1/k_1 + 1/M_1$; $\Delta_2 = 1/k_2$; $k_1 \approx k_2 \approx k_3 \approx k$ are transmission coefficients of $DA1$, $DA2$ and inverter IN, respectively; e_1, e_{211} are equivalent AEC on the input and output of the calibrator in the first cycle (on the top input S_{12} in Fig. 3); M_1 is the coefficient of relaxation of the common-mode component $DA1$; Δ_μ is the absolute error of *CCVD*.

If the transmission coefficients $DA1$, $DA2$ are approximately the same $k_1 \approx k_2 \approx k_3 \approx k$ then the output voltage of the inverter IN U_{K12} is given by the following expression:

$$U_{k12} = \left(E_{N1} + e_1\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_3\right) + e_{212}, \qquad (3)$$

where $\Delta_3 = 1/k_3 + \Delta_{R12}$; $\Delta_{R12} = \Delta_{R1} + \Delta_{R2}$; Δ_{R1}, Δ_{R2} are instrumental errors of the inverter IN feedback resistors; e_{212} is the equivalent AEC at the output of the inverter IN in the first tact (at the bottom input S_{12} in Fig. 3).

Taking into account the remaining parameters of the keys, the storage capacitor C will be charged to the voltage difference, respectively, U_{C11} and U_{C12}:

$$U_{C11} = -\left(E_{N1} + e_1\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_2\right) + e_{211} + \Delta_{11}, \qquad (4)$$

$$U_{C12} = \left(E_{N1} + e_1\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_3\right) + e_{212} + \Delta_{12}, \qquad (5)$$

where $\Delta_{11} = (I_{B1} + I_{B4}) r_{k1}$, $\Delta_{12} = (I_{B2} + I_{B3}) r_{k2}$ are equivalent AEC due to the reverse currents of the closed switches, respectively, SW_1 and SW_2 of the polarity switch S_{12}; I_{B1}, I_{B2}, I_{B3}, I_{B4} are reverse currents of the keys, respectively, SW_1, SW_2, SW_3, SW_4; r_{k1}, r_{k2} are the resistance of closed keys SW_1 and SW_2; e_{221} is the equivalent AEC at the output of the calibrator in the second stroke (on the upper input S_{12} in Fig. 3); e_{222} is the equivalent AEC at the output of the inverter IN in the second tact (at the bottom input S_{12} in Fig. 3).

The storage capacitor C in the second half-period when connected to the DCVC input of the second RVS will be charged to the voltage difference, respectively, U_{C21} and U_{C22}:

$$U_{C21} = \left(E_{N2} - e_1\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_2\right) + e_{221} + \Delta_{21}, \qquad (6)$$

$$U_{C22} = -\left(E_{N2} - e_1\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_3\right) + e_{222} + \Delta_{22}, \qquad (7)$$

where $\Delta_{21} = (I_{B2} + I_{B3}) r_{k3}$, $\Delta_{22} = (I_{B1} + I_{B4}) r_{k4}$ are equivalent AEC due to the reverse currents of the closed switches, respectively, SW_3 and SW_4 of the polarity switch S_{12}; r_{k3}, r_{k4} are the resistance of the closed keys SW_3 and SW_4. Δ_{E2} is the relative error of RVS E_{N2}.

Taking into account that during one transformation of the offset voltage, $e_{211} \approx e_{212}$ and $e_{221} \approx e_{222}$ are unchanged, the total values of the voltages on the capacitor C in each of the half-periods are given by the expressions:

$$U_{C1} = U_{C11} - U_{C21} = \left(E_{N1} + E_{N2}\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_2\right) + \left(\Delta_{11} - \Delta_{21}\right), \qquad (8)$$

$$U_{C2} = U_{C12} - U_{C22} = = \left(E_{N1} + E_{N2}\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+\delta_3\right) - \left(\Delta_{12} - \Delta_{22}\right). \qquad (9)$$

The output voltage DCVC is defined as the mean value of the voltage on the capacitor C for the period of switching frequency:

$$U_k = U_{C1} - U_{C2} = = 2\left(E_{N1} + E_{N2}\right)\left(1+\delta_1\right)\left(\mu + \Delta_\mu\right)\left(1+1/\delta_3\right) + +\left[\left(\Delta_{11} - \Delta_{21}\right) - \left(\Delta_{12} - \Delta_{22}\right)\right], \qquad (10)$$

where

$$(\Delta_{11} - \Delta_{21}) - (\Delta_{12} - \Delta_{22}) = = (I_{B2} + I_{B3})(r_{k1} + r_{k3}) - (I_{B1} + I_{B4})(r_{k2} + r_{k4}).$$

The analysis of the expression (10) shows that the unadjusted value of the additive error component of the DCVC will be determined by the instrumental error components of the output polarity switch S_{12}. The instrumental error components will be determined only by the difference between the products of sums of the pair of resistance of the closed keys and the sums of the inverse currents of the keys of both polarity switches.

6. Results of simulation of the calibrator circuit operation

Computer simulation of the proposed scheme of the DC voltage calibrator with automatic adjustment of the AEC by the method of switching inversion is carried out in the application package according to the model presented in Fig. 4.

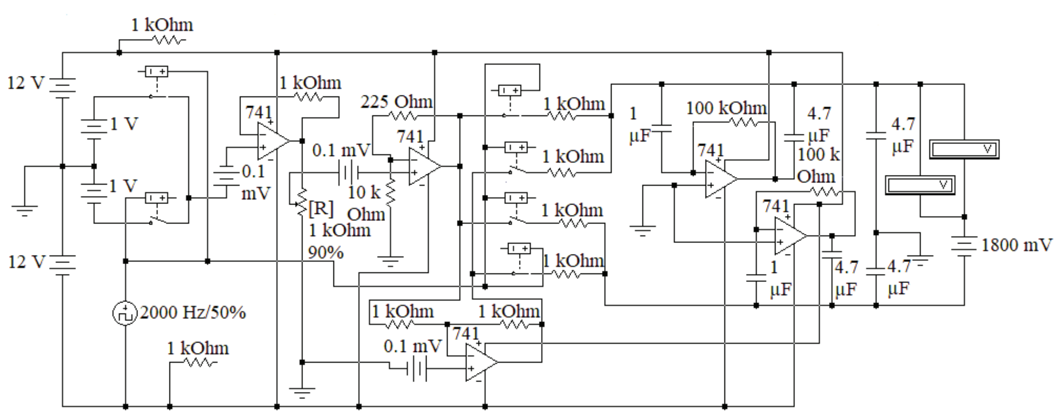

Fig. 4. Scheme for simulation of DC voltage calibrator with automatic adjustment of additive offsets

The simulation was carried out by setting nine values of the DCVC separation coefficient from 10 % to the maximum value with a 10 % step. In this case, the parameters of the DCVC without (U_K) and with (U_{KAEC}) were recorded for connection to certain inputs of the SNF elements of the additive offset simulator (Table 1). There were differences between the corresponding maximum values $\Delta Uk=U_K-U_{KASS}$ when connecting the additive offset simulator to different points of the DCVC (Fig. 4). The simulation was carried out for different values of frequencies (0.5 kHz, 1 kHz and 2 kHz) of switches. As a result of mathematical modeling, it is found that the degree of correction does not depend on the place of connection of the additive offset simulator to the DCVC scheme.

Table 1

Difference of output voltages of the computer model of the voltage calibrator with error correction with the clock generator frequency of 1 kHz

Separation factor CCVD, %	U_C, V	U_{CAEC}, V	$\Delta U_C=U_C-U_{CAEC}$, V
10	0.200278	0.200274	0.000004
20	0.400285	0.400278	0.000007
30	0.600325	0.600333	–0.000008
40	0.800315	0.800326	–0.000011
50	1.000387	2.00377	0.000010
60	1.200398	1.200411	–0.000013
70	1.400431	1.400415	0.000016
80	1.600462	1.60043	0.000019
90	1.800456	1.800433	0.000023

The minimum value of the output voltage differences of the computer model of the voltage calibrator is at a frequency of about 1 kHz.

7. Results of experimental studies of the model of the DC voltage calibrator with automatic error correction

The scheme of experimental studies of the DCVC layout with AEC adjustment consisted of the layout of voltage calibrator, precision voltmeter B for controlling the supply voltage and measuring the output voltage Uv of the calibrator (multimeter M3514A No. TW0013442, PICOTEST company), frequency meter Freq and oscilloscope Osc (oscilloscope Rigol DS1202CA head number DS1AB113000314, frequency meter Ch3-54 head number 8711069) to measure the frequency and control the signal shape of the clock generator. Experimental studies of the DCVC model with AEC adjustment were carried out at different frequencies of the clock generator of 100 Hz, 300 Hz, 600 Hz, 1.2 kHz, 2.5 kHz, 5.0 kHz. The study was conducted without the use of simulator AEC and using the simulator AEC. At the same time, the value of the simulator voltage ACP was 10 mV, which is approximately equal to the equivalent zero-level offset voltage used in the layout of the CCVD of operational amplifiers. Accordingly, the simulator AEC was connected to different amplifier inputs, and the maximum errors were recorded. The maximum error values were determined as the difference between the readings of the digital voltmeter with switched off and on simulator ONP.

The results of the experimental studies of the model showed that the smallest values of the errors of the model of the voltage calibrator with AEC adjustment were at the 1.2 kHz clock generator frequency (Table 2).

Table 2

Difference of output voltages of the model of the voltage calibrator with additive error correction with the clock generator frequency of 1.2 kHz

U_{CCVD}, V	U_C, V	U_{CAEC}, V	$\Delta U_k=U_K-U_{CAEC}$, V
0.0	0.000005	0.000011	–0.000006
0.5	0.484721	0.484713	0.000008
1.0	0.981985	0.981976	0.000009
1.5	1.47537	1.47527	–0.000010
2.0	1.97854	1.97844	0.000010

The variation of differences of the output voltages of the voltage calibrator model with the additive error correction along the reproduction range within ±10 μV can be explained by two factors. The first of these is the use of relatively high-ohm passage resistors in the LPF, which made the external layout more effective. The second factor is due to the change in the least significant digit of the precision voltmeter during automatic switching of its measuring subbands.

8. Discussion of experimental results of the voltage calibrator layout

The appropriateness of automatic adjustment of the AEC in the DCVC is experimentally confirmed, which provides a significant reduction of the unadjusted value of the additive offsets. In this case, the design of the DCVC has such a configuration that the values of converted voltages do not exceed the value of 4 V, which makes it easy to reconcile them with the microelectronic components for the construction of calibrators. It also allows the DCVC to be implemented as an integral microcircuit without using a large number of external precision scalable components [20].

Proposed techniques for adjusting the multiplicative error component (MEC) of the DCVC can be implemented by software. In this case, only a few keys can be used to enter information about the sign of the gauge value.

The studies allow the implementation of precision intelligent voltage calibrators, the metrological characteristics of which will exceed the characteristics of the commercially available combined multi-valued measures MK4702, OJSC «Microprylad», Lviv (Ukraine). The DC voltage can be reproduced in sub-bands 0 to +100 mV with a discretion of 1 μV, 0 to +1 B with a discretion of 10 μV, 0 to +10 V with a discretion of 100 μV and tolerance of ±0.05 % [21]. The results of the research have shown that the technical characteristics of calibrators with auto-calibration may be better than those of commercially available portable voltage calibrators. When applying RVS thermostabilization, or measuring its temperature by built-in channels, with the subsequent introduction of corrections, the limit of admissible values of the DCVC error can be reduced to ±(0.01...0.02) %. For the implementation of embedded temperature measurement channels, inexpensive digital temperature meters [22] developed by the authors can be used. The developed DCVC can be used as portable devices in the field of power engineering, in the oil and gas complex, in the communal sector, agriculture, food industry, etc. On the basis of the developed structure of the DCVC with minimal hardware costs, a code-controlled resistance simulator with the correction of the additive offsets by the method of double switching inversion can be implemented [23].

The applied experimental research methodology meets the requirements of a number of normative documents: Technical regulations for measuring instruments No. 163; Technical regulations for legally regulated measuring instruments No. 94; DSTU 2708: 2006 «Metrology. Verification of measuring equipment. Organization and procedure»; DSTU ISO 10012: 2005. «Requirements for measurement processes and measuring systems».

The narrow range of reproducible voltages of the experimental studies and somewhat cumbersome method of adjusting the MEC DCVC can be attributed to the disadvantages of the results obtained. In addition, the results of experimental studies were influenced by external obstacles, as the mockup was tested without the use of constructive and technological measures to reduce the influence of non-informative parameters. Solving these problems is the main task of further research.

9. Conclusions

1. Theoretical assumptions about the effectiveness of the method of switching inversion for the automatic correction of the additive error component of portable DC voltage calibrators are in good agreement with the results of experimental studies within several least significant digits of the used digital voltmeter.

2. The developed structure of the calibrator consists of a reference voltage source, input and output polarity switches, which work synchronously, the code-controlled voltage divider and two voltage repeaters. The unadjusted value of the additive offsets is determined by the spread of the parameter values of both pairs of the closed keys of polarity switches.

3. As shown by the analysis of the experimental results, in the developed structure the values of the voltages reproduced by the calibrator model do not depend on the voltage value and the location of the offset voltage simulator.

4. In the manual control mode, the uncorrected value of the additive error component does not exceed ±1 μV (least significant digit of the precision digital voltmeter) for all reproduced values of the output voltage of the model.

5. Analysis of the results of experimental studies of the voltage calibrator model at different frequencies of the clock generator showed that the minimum uncorrected value of the additive error component is at the clock generator frequency about 1.2 kHz. At this frequency, the uncorrected value of the additive error component of the DC voltage calibrator model is within ±5 μV (within several least significant digits of the precision digital voltmeter). To reduce this value several times (up to ±1 μV), it is necessary to increase the time constant of the output filter of the voltage calibrator.

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