AC VOLTAGE UNIT STANDARD BASED ON THERMOELECTRIC CONVERTERS

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- *The results of testing thermal converters of TVB and DTPT type for stability and heteropolarity error, as well as the ways of schematic and algorithmic improvement due to their incorporation in AC voltage unit standard from 0.1 to 1000 V in the frequency range from 10 Hz to 30 MHz, developed at NTTU "KPI" Research and Development Institute for Experimental Research Automation, are represented.*

Introduction

It is a topical matter to assure the traceability of measurements based on a system of national and primary standards assuring reproduction of a certain physical quantity and transfer the size of its unit to working and/or references standards from which the size of this quantity unit is transferred to working measuring instruments. One must constantly improve the systems of measurement, control and test in the development, production and application of products.

As is known, a standard must have the highest metrological characteristics of this unit measuring instruments existing in the state, at the enterprises, in organizations or institutions [1, 2]. The highest metrological characteristics of the standard are assured due to various precision improvement methods, namely: design-technological, protective-preventive and structural-algorithmic. In other words, a set of standard equipment should comprise components possessing high precision, reliability and often multifunctionality. In so doing, the cost of equipment employed is a major criterion.

Today the national standard of alternating current in Ukraine does not assure current reproduction in a very important for radio engineering devices frequency range 1 MHz to 30 MHz at voltage levels up to 30 V. Moreover, the national standard of Ukraine is periodically calibrated in Germany. Therefore, creation of AC voltage unit standard for a wide frequency range is a relevant task.

AC voltage is a rather complicated quantity, since there is no physical phenomenon that would create a root-mean-square value of AC voltage

$$U_{RMS}=\sqrt{\frac{1}{nT}\int_{0}^{nT}U^{2}\left(t\right)dt}\,, \tag{1}$$

where T is signal period, n is the number of periods, $U(t)$ is time dependence of voltage.

In the majority of National Metrology Institutes [3] the reproduction of alternating voltage unit is based on the process of its comparison to known DC voltage value, that is, transfer of small uncertainty of DC voltage unit to alternating current.

The distinguishing feature of the national standards in different countries lies in the substantiation of the errors of reproduction of AC voltage root-mean-square value.

The main sources of errors for standards of thermal comparator type are [4, 5]:

- the error of transition from DC to AC voltage which is due to fundamental Thomson and Peltier effects;

- frequency error caused by the influence of eddy currents, the presence of reactive components of resistance both in thermal converters themselves and in additional resistances, connecting elements, switches, etc;
- the error of time-heterogeneous comparison, caused by comparison of DC and AC voltages at different time moments;
- the error of reproduction of DC voltage which is used as a transferred unit of DC voltage root-mean-square value;
- the total error of other components of equipment set whereby transfer of unit from DC to AC voltage is realized.

By joint efforts of Institute of Thermoelectricity (Chernivtsi) and Yu. Fedkovych Chernivtsi National University there have been developed and introduced into production the basic designs of series of semiconductor differential current (DTP) and voltage (DTPN) converters [6]: DTP503-(1–5) (comparison error at frequencies $\leq 0.003\%$ (1 KHz), $\leq 0.005\%$ (20 Hz – 100 kHz)), DTPN-2401–2403 (comparison error at frequencies $\leq 0.003\%$ (1 KHz), $\leq 0.01\%$ (20 Hz – 100 kHz), $\leq 0.3\%$ (100 kHz – 30 MHz)), DTP-1305 (comparison error at frequencies $\leq 0.01\%$ (20 Hz – 100 kHz), $\leq 0.02\%$ (100 Hz – 200 kHz), $\leq 0.1\%$ (20 kHz – 1 MHz)).

A set of electrothermal converters V9-14 was developed and introduced into production at the Federal State Unitary Enterprise NNIPI “Kvarz” for high-precision measurement of low and high-frequency AC voltage signals [7] instead of outdated products PNTE-6 and PNTE-12, which do not require the use of auxiliary equipment (microvoltmeters and DC voltage calibrators), have low heat retention and are resistant to considerable overloads, as well as possess high metrological characteristics: the limit of permissible main conversion error 0.01%, frequency range 10 Hz to 200 MHz.

The accuracy of measuring AC values depends on the quality of thermoelectric converters.

In thermal converters that are used for metrological purposes the heater and thermocouple are close in geometrical dimensions, so the thermocouple thermal conductivity has a very significant effect on the temperature distribution along the heater. To characterize the thermal converter, the concept of volt-watt sensitivity S_w has been introduced which takes into account thermophysical processes occurring in the thermocouple:

$$S_{KE} = \frac{Z_T \Delta T}{4F} = \frac{\alpha^2 \sigma_T \Delta T}{4\kappa_T F}, \tag{2}$$

where σ_T is the electrical conductivity of thermocouple material, Z_T is the thermoelectric figure of merit of thermocouple material, F is a coefficient which characterizes the rationality of using heat in thermal converter design.

Formula (2) corresponds to the expression for the efficiency of thermoelectric generator at low temperature differences on thermoelements and on the assumption that thermocouple material parameters do not depend on temperature. The expression for S_{KE} can be written more precisely in the form

$$S_{KE} = \frac{\Delta T\sqrt{1+ZT} - 1}{(T_T\sqrt{1+ZT} - \frac{T_c}{T_h})F}. \tag{3}$$

Here T_c and T_h are the cold- and hot-junction temperatures of the thermocouple.

From the analysis of formulae (2) and (3) it follows that the main operating parameters of thermoelectric converter are assigned by the thermoelectric figure of merit of thermocouple material

Z_T, the operating temperature difference ΔT and coefficient F.

Nowadays, considerable improvement of the operating and metrological parameters of thermal converters is only possible due to increase in thermoelectric figure of merit of thermocouple material Z_T. With a growth of Z_T, the converter's sensitivity is increased. This increase is particularly essential with a transition from metal to semiconductor alloys. For instance, if for chromel-copel the sensitivity $S_w = 4.2$ V/W, for Bi_2Te_3 alloys it reaches 92 V/W, i.e. it is increased by a factor of almost 20. There is a similar increase in parameters R, S_{KE}, E_T which are used for the estimation of thermal converters.

The possibility of increasing the sensitivity of thermoelectric converters with the use of semiconductor materials possessing high Seebeck coefficient α is also indicated in the work by T.B. Rozhdestvenskaya [8].

The use of semiconductor materials creates favourable prerequisite for making converters with limiting sensitivity values that are restricted by fluctuation noise only.

An important characteristic that governs the accuracy and operating opportunities is temperature error. It is determined by the value of a relative change in output thermoEMF with a variation of ambient temperature:

$$\delta_t = \frac{E_{t_2} - E_{t_1}}{E_{t_1}(t_2 - t_1)} 100\%, \tag{4}$$

where E_{t_2}, E_{t_1} are converter's thermoEMFs that correspond to temperatures t_2, t_1.

The following expression is used to describe the temperature dependence of thermal converters' thermoEMF:

$$E_t = \alpha_T \frac{R_H}{R_H R_T} \frac{I_H^2 \rho l^2}{2d^2 R_0} [1 + (Z\alpha - M\beta - NT_0^2 + P\gamma) I^2], \tag{5}$$

where α_T is the Seebeck coefficient of the thermocouple, R_T is the thermocouple resistance, R_H is the heater resistance, ρ is the heater resistivity, l is the heater length, d is the heater cross-section, R_0 is the heater thermal conductivity, α is the heater temperature coefficient of resistance, β is the temperature coefficient of thermal conductivity, T is the ambient temperature, γ is the temperature Seebeck coefficient of thermocouple, Z, M, N, P are the members describing temperature variation due to a change in the heater resistance, a change in the heater thermal conductivity, radiation, a change in the thermocouple thermal conductivity; they are not cited here because of the awkwardness.

Analysis of expression for the temperature dependence of thermoEMF shows that the greatest contribution to temperature error is made by temperature properties of the heater and thermocouple materials; changes due to radiation temperature dependence are of minor importance.

Of materials used for manufacturing material heaters, manganin has the lowest temperature dependence of parameters. However, in the constructions of thermal converters with metal thermocouples manganin heaters are not employed. It is due to the following reasons: *a*) on heating above 120°C, irreversible changes take place in manganin leading to modification of resistivity and temperature coefficient; *b*) the value of manganin resistivity does not allow forming short high-resistance heaters.

Converters with thermoelements of semiconductor materials offer one basically important advantage over metal ones, namely achievement of the necessary output signal 10 ÷ 15 mV is possible at much lower heater overheat (10 ÷ 20°C).

To assure insignificant temperature error, the semiconductor material should be optimized in such a way as to compensate temperature changes of thermocouple junction which is heated by manganin heater with a change in ambient temperature and to assure the constancy of output thermoEMF in given temperature range (for instance, –5 ÷ 35°C). That is, for the temperature properties of the heater and thermocouple the following equation must be met:

$$\frac{\rho_H}{\kappa_H}(t)+\frac{\alpha_T}{\kappa_T}=c, \tag{6}$$

where ρ_H is the resistivity of heater material, κ_H is the thermal conductivity of heater material, α_T is the Seebeck coefficient of thermocouple material, κ_T is the thermal conductivity of thermocouple material, t assumes the value of 50 to 60°C, c is a constant.

The DTPT-6 converters employ heaters of manganin microwire and thermocouples of optimized semiconductor material, which enables the DTPT-6 thermal converters to be used when constructing the reference voltage converters.

Guided by the world trends and the national requirements in the matter of completeness of a system of standards of electrical quantities in general and the accuracy of measuring the AC electrical values, in particular, the team of NTTU “KPI” Research and Development Institute for Experimental Research Automation has elaborated a military secondary standard of electrical voltage unit from 0.1 to 1000 VAC in the frequency range of 10 Hz to 30 MHz.

1. Testing TVB and DTPT-6 converters for stability and heteropolarity error

The main unit of voltage standard of thermal comparator type is thermoelectric voltage converter. Complete sets of exactly such converters (EPNTE and PPNTE) were elaborated at NTTU “KPI” Research and Development Institute for Experimental Research Automation.

A complete set of EPNTE is used for thermal comparison of DC voltage to AC voltage. The EPNTE are standards for comparison to other standards and consist of series-connected additional resistor, PNTE of DTPT-6 type and additional resistance mounted in one case.

A complete set of PPNTE is intended for use in unsteady conditions. Structurally, PPNTE coincide with EPNTE, with the difference that PPNTE employ PNTE of TVB-3 type, rather than PNTE of DTPT-6 type.

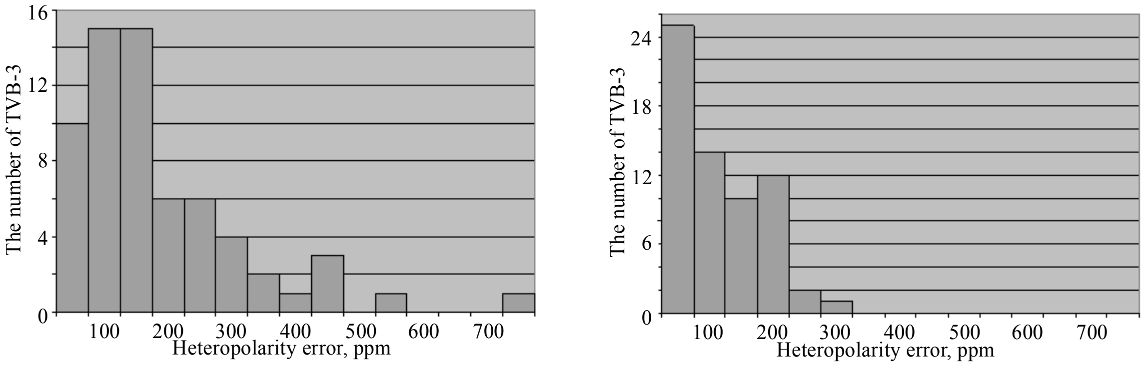
Both complete sets employ specially selected thermal converters based on the minimum asymmetry error with the effect of heteropolar voltage and maximum short-term stability. Insulations made of high heat-conducting ceramics contribute to short-term stability.

In the creation of these complete sets, design-technological methods of accuracy improvement were used which include nonstability and heteropolarity criteria [9, 10]. These criteria were used to determine whether this or that thermal converter under study can become part of EPNTE and PPNTE. In so doing, acceptable types of the most widespread thermal converters were considered, such as vacuum unicouple converters of the type TVB-3 and TVB-4; differential thermal converters DTPT-6; thermoelectric voltage converters PNTE-6 based on vacuum unicouple converters of TVB type; multi-element film thermal converter RTV; thermoelectric voltage converters PNTE-12, thermoelectric voltage converters PNTE-12/2, elaborated standard thermoelectric voltage converters of different ratings. TVB-3, TVB-4 and DTPT-6 were analyzed for the purpose of “screening” and tested for yield ratio of each thermocouple type whose heteropolarity and stability criteria would be acceptable to become part of EPNTE and PPNTE.

1.1. Study of vacuum unicouple converters of TVB type

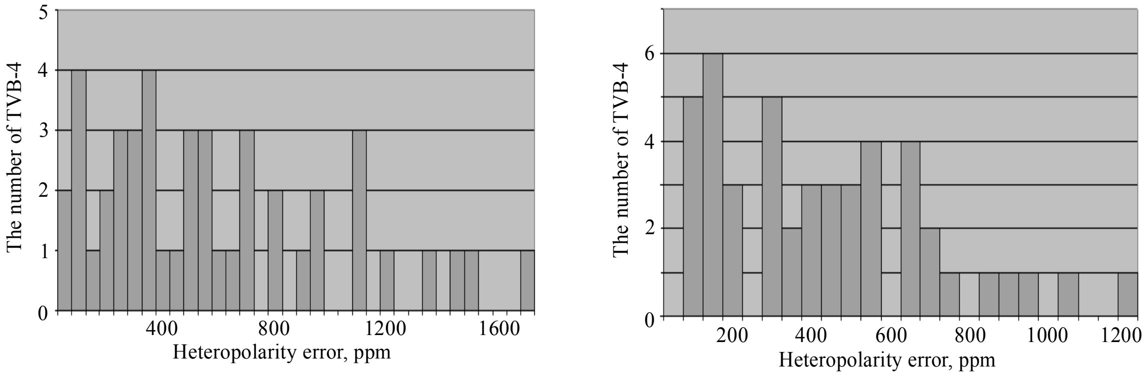
Vacuum noncontact thermal converters (TVB) due to their broadbandness have gained wide acceptance during reproduction and transfer of AC volt unit. One of the most essential TVB drawbacks is inequality of output thermoEMF with a change in polarity of equal value direct current because of the Thomson and Peltier effects. In thermal comparison mode this causes the error of transfer of DC to AC value.

The TVB-3, TVB-4 lots were tested for heteropolarity error at rated currents 1.0 I_r 0.5 I_r and 0.3 I_r. The differential and integral histograms of errors were obtained (Fig. 1 – 4), from which it is evident that only 10% TVB have heteropolarity error less than 100 ppm, 20% less than 200 ppm, 50% less than 500 ppm, that is, the number of TVB suitable for use in standard equipment is very small.



a) *b)*

Fig. 1. Differential histogram of TVB-3 heteropolarity error at 3 mA (a) and 5 mA (b).



a) *b)*

Fig. 2. Differential histogram of TVB-4 heteropolarity error at 5 mA (a) and 10 mA (b).

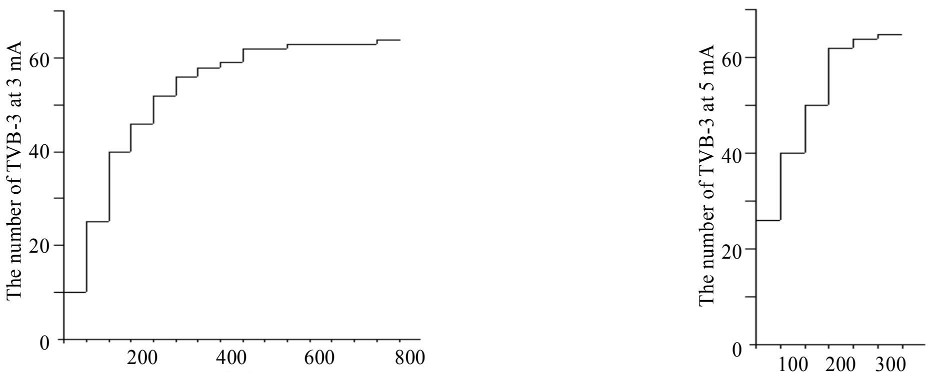


Fig. 3. Integral histogram of TVB-3 heteropolarity error at 3 mA and 5 mA.

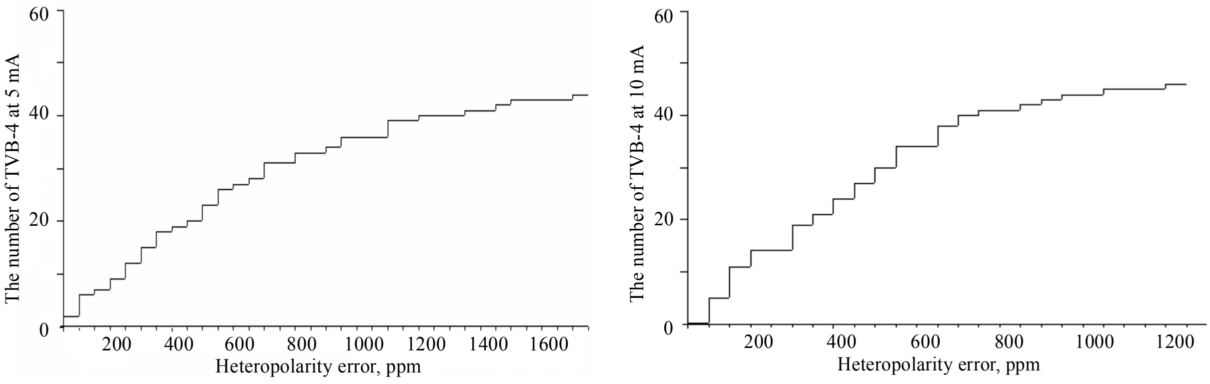
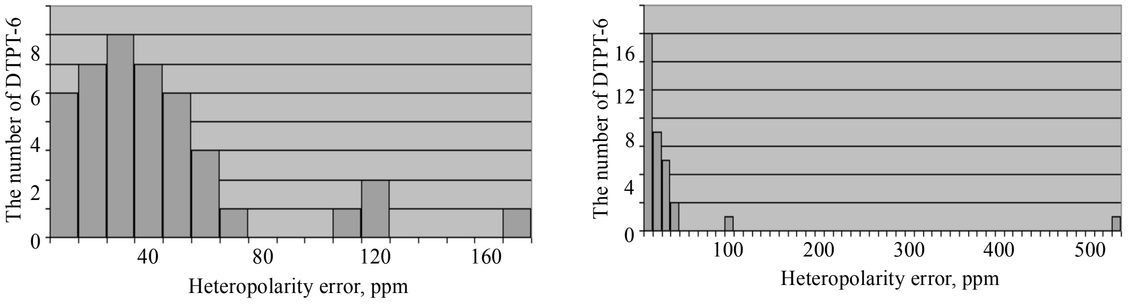


Fig. 4. Integral histogram of TVB-4 heteropolarity error at 5 mA and 10 mA.

1.2. Study of differential thermal converters of DTPT-6 type

The lots of DTPT-6 were also tested for heteropolarity error at rated voltages 5 V and 8 V (with currents 5 mA and 8 mA, respectively).



a) *b)*

Fig. 5. Differential histogram of DTPT-6 heteropolarity error at 5 V and 8 V.

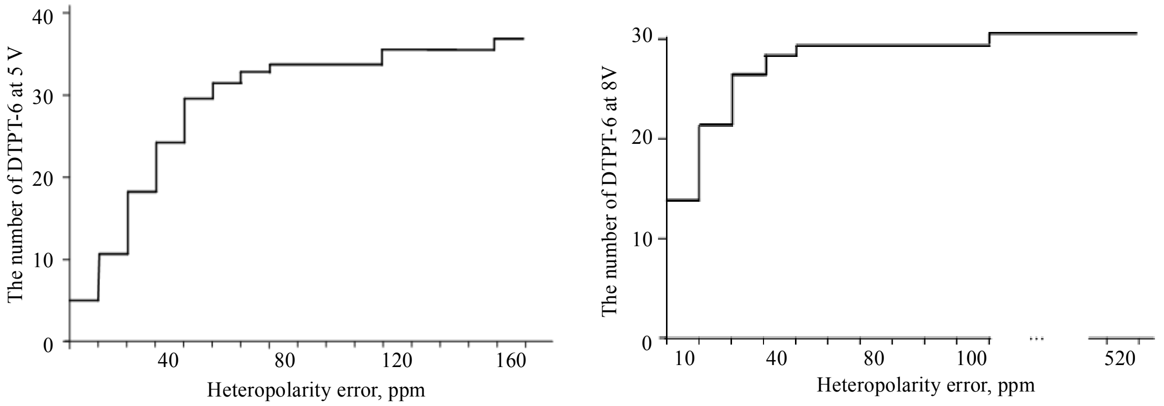


Fig. 6. Integral histogram of DTPT-6 heteropolarity error at 5 V and 8 V.

Analysis of differential and integral histograms of heteropolarity errors (Fig. 5 – 6) has shown that nearly 80% of DTPT-6 have heteropolarity error less than 100 ppm, which is much better than for TVB. So, they were used in the manufacture of EPNTE complete set.

1.3. Approaches used for reduction of errors

To reduce heteropolarity error, it was proposed to realize a series or parallel connection of heaters of two unicouple converters with close but opposite heteropolarity errors and a series connection of thermocouples. With a large number of thermal converters one can compensate heteropolarity errors in the couples and use almost all thermocouples, thus obtaining the number of standard converters equal to half of those available.

Another drastic method of reducing the error of transition is calibration of thermal converters by voltage of known shape, the effective value of which can be calculated analytically. The NTTU "KPI" Research and Development Institute for Experimental Research Automation has patented voltage converter per time interval allowing the necessary calibration and amendment to be made individually for each TVB [11].

To minimize the frequency error, an improvement was introduced into PNTE design, where the inductive component of resistance was minimized. An automatic system using multiplicative algorithm was created to determine the difference in PNTE frequency errors, owing to which the requirements to stability of AC voltage sources were reduced.

Parameters of DC voltage meters have been improved considerably. Their resolution has been brought to 100 pV, the basic error has been reduced to ppm units.

It makes possible to work at lower thermoEMF and to expand the dynamic range.

A contradiction between the instability and setting time is reduced by refusal from zero thermal comparison and measurement in the vicinity of the set value with calculation of polynomial approximant coefficients for the positive and negative parabola legs, as well as by finding the value of AC voltage an the averaged root of polynomial approximants.

The results of experimental studies on the stability of conversion coefficients for TVB-3 are represented in Fig. 7, for TVB-4 – in Fig. 8, for DTPT-6 – in Figs. 9 – 12.

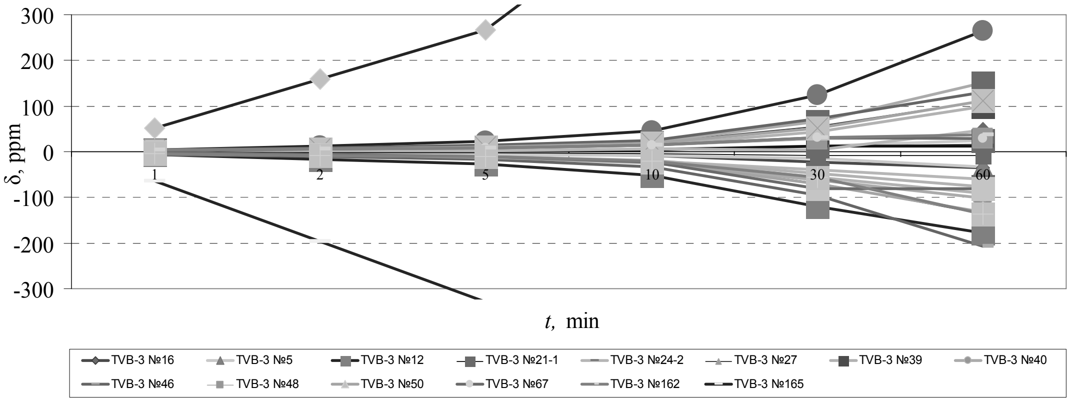


Fig. 7. Plot of averaged deviations of conversion coefficients versus observation time for TVB-3.

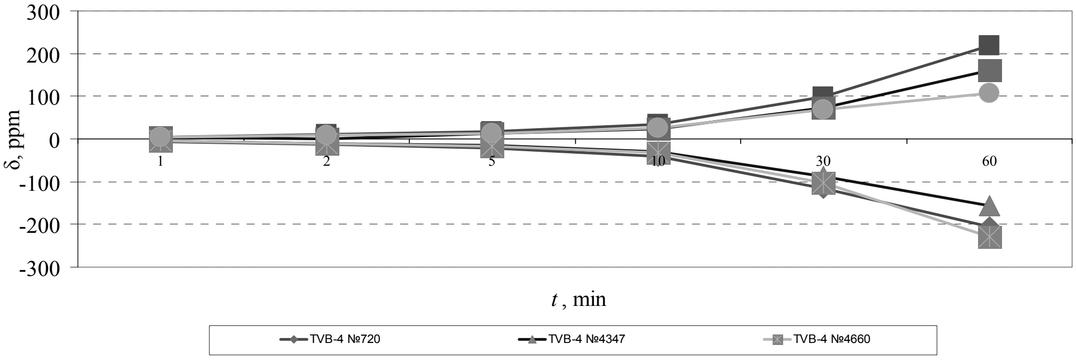


Fig. 8. Plot of averaged deviations of conversion coefficients versus observation time for TVB-4.

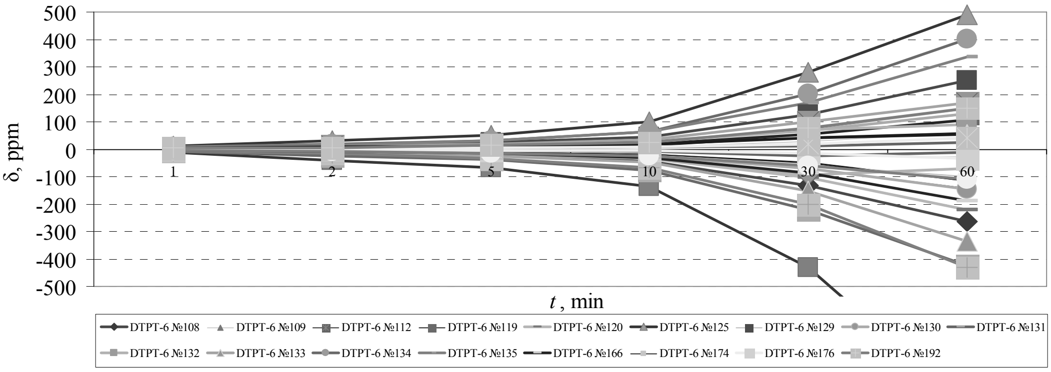


Fig. 9. Plot of averaged deviations of conversion coefficients versus observation time for DTPT-6 (5 V, 1-st heater).

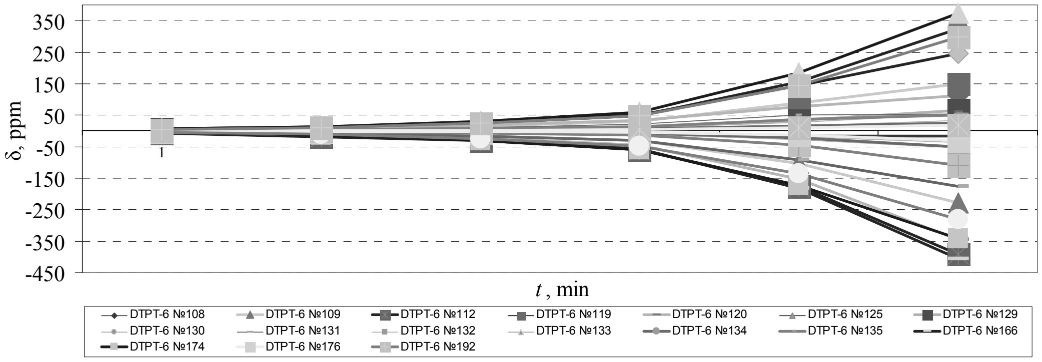


Fig. 10. Plot of averaged deviations of conversion coefficients versus observation time for DTPT-6 (5 V, 2-nd heater).

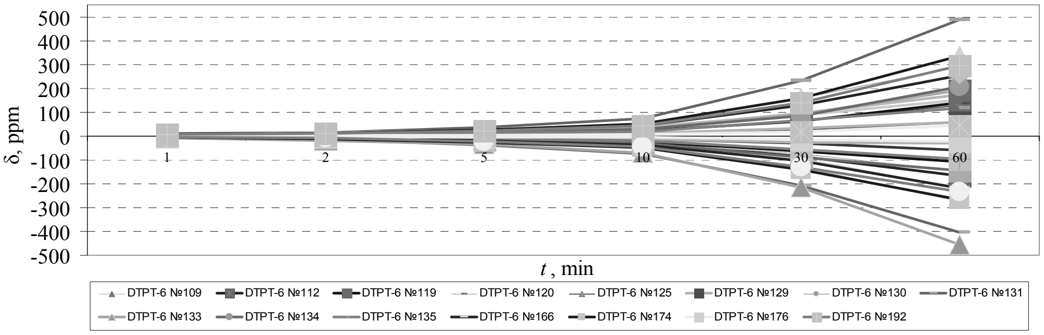


Fig. 11. Plot of averaged deviations of conversion coefficients versus observation time for DTPT-6 (8 V,1-st heater).

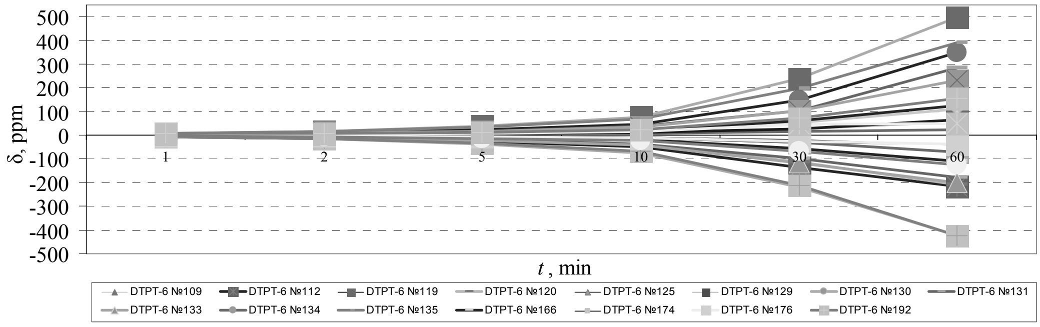


Fig. 12. Plot of averaged deviations of conversion coefficients versus observation time for DTPT-6 (5 V, 1-st heater).

2. Military secondary standard of electric voltage unit from 0.1 to 1000 VAC in the frequency range from 10 Hz to 30 MHz

The elaborated military secondary standard of electric voltage unit from 0.1 to 1000 VAC in the frequency range from 10 Hz to 30 MHz is used to perform certification, verification and calibration of first grade working standards for thermoelectric voltage converters, calibration setups, calibrators of precision, selective multi-purpose, combined voltmeters, generators of low-frequency and high-frequency signals.

Military standard is a self-consistent automated system which does not require calibration from other AC voltage standards, consists of equipment set united by real-time interface: precision DC and AC voltage sources, supersensitive high-precision DC voltage meters, spectrum analyzer, device for automatic recording and processing of measured results, etc.

The content of the equipment and standard general view are shown in Fig. 13.

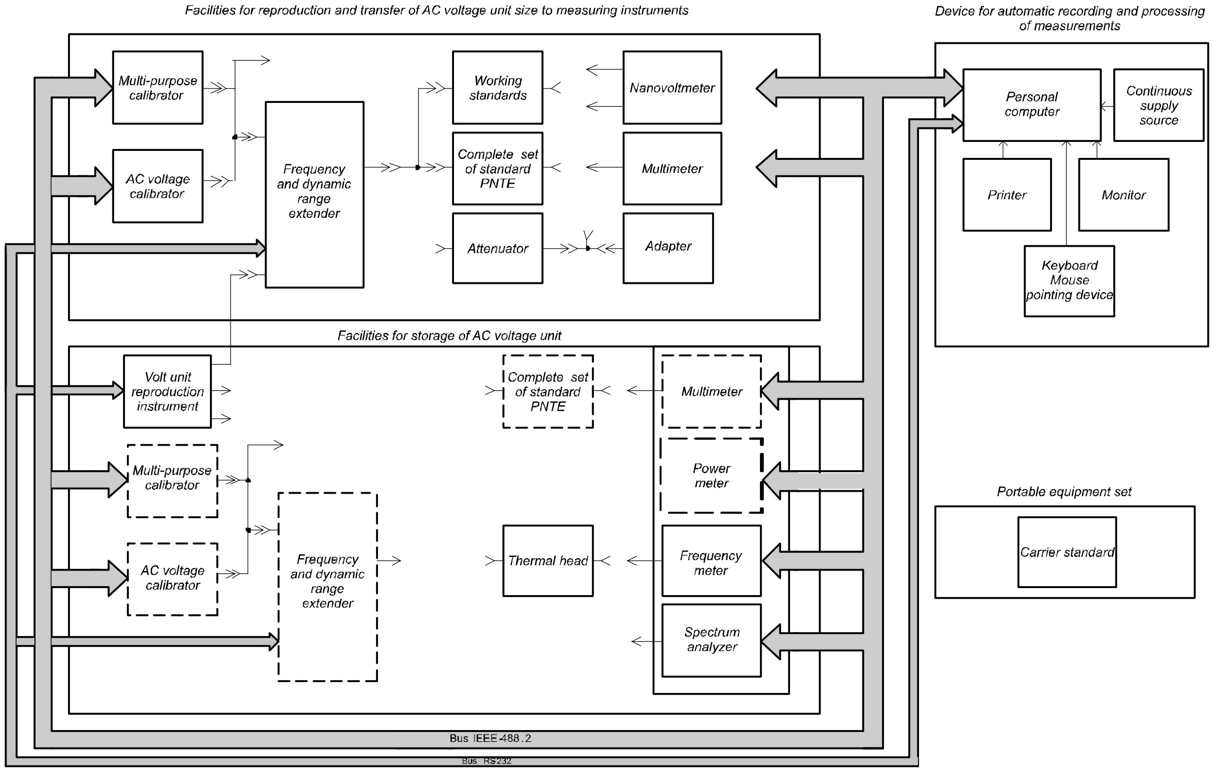


Fig. 13. Complete equipment of AC voltage unit standard developed at NTTU "KPI" Research and Development Institute for Experimental Research Automation. Schematic diagram.

The equipment set includes the following unique measuring instruments developed at the NTTU "KPI" Research and Development Institute for Experimental Research Automation:

1) frequency and dynamic range extender (BRChDD) comprising three amplifiers:
   - BRChDD1 – frequency range up to 30 MHz, RMS voltage range up to 30 V, signal slew rate 10000 V/ms;
   - BRChDD2 – frequency range up to 1 MHz, RMS voltage range up to 100 V, signal slew rate 1000 V/ms;
   - BRChDD1 – frequency range up to 100 kHz, RMS voltage range up to 1000 V, signal slew rate 1000 V/ms;
2) measuring unit to determine ac-dc error, generating voltage at frequency 1 kHz with

nonlinear distortions less than 3 ppm;

3) complete set of standard thermoelectric voltage converters (EPNTE) with voltage rated limits 1, 2, 4, 8, 16, 32 V (Fig. 14, 15);
4) complete set of portable thermoelectric voltage converters (PPNTE) with voltage rated limits 0.5, 1, 2, 4, 8, 16, 32 V (Fig. 14, 16)

Fig. 14. External view of a complete set of standard (left) and portable (right) thermoelectric voltage converters developed at NTTU "KPI" Research and Development Institute for Experimental Research Automation.

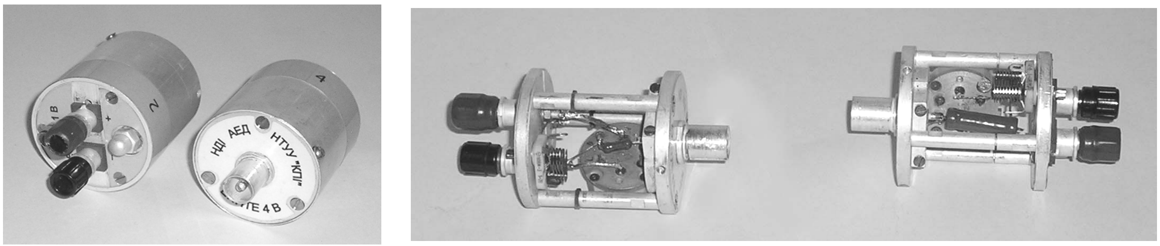


Fig. 15. General view of individual EPNTE and individual uncased PNTE.

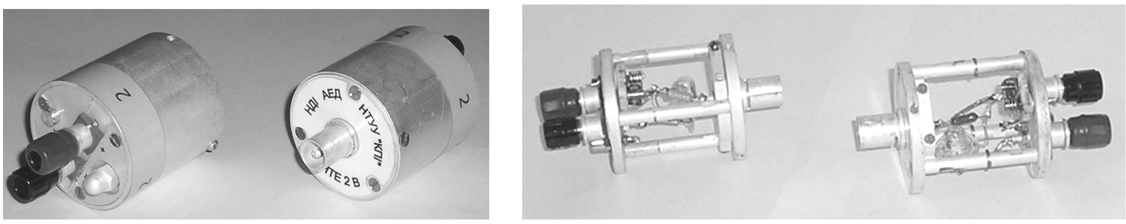


Fig. 16. General view of individual PPNTE and individual uncased PPNTE.

In so doing, procedures, algorithms and software have been elaborated:

- to solve the problem of digital stabilization of output signals of calibrators and amplifiers with the use of iteration algorithms, which minimizes the time of given level setting and reduces requirements to signal sources;
- to determine heteropolarity error;
- to determine maximum deviation with given parameter probability of devices (thermal converters, amplifiers, calibrators, etc.) from the mathematical average depending on observation time;
- to determine the difference in frequency characteristics of standard and calibrated PNTE;
- to determine the error of transition from DC to AC voltage of calibrated PNTE as regards the standard;
- to perform self-calibration of EPNTE without comparison to national standard.

Conclusions

1. A combination of algorithmic and schematic solutions has allowed increasing the accuracy and broadbandness of PNTE through use of commercial TVB.
2. According to the results of research, the yield ratio for TVB-3 thermocouples is relatively high; for TVB-4 it is low, for DTPT-6 – high.
3. According to the results of research, the following differential thermal converters DTPT-6 have been incorporated in standard thermolectric voltage converters: EPNTE E0.5 – DTPT-6 №131-1; EPNTE E1 – DTPT-6 №174-1; EPNTE E2 – DTPT-6 №134-2; EPNTE E2-1 – DTPT-6 №125-2; EPNTE E4 – DTPT-6 №176-1; EPNTE E8 – DTPT-6 №192-2; EPNTE E16 – DTPT-6 №133-2; EPNTE E32 V – DTPT-6 №129-2.
4. According to the results of research, the following vacuum unicouple converters of TVB-3 type have been incorporated in portable thermoelctric voltage converters: PPNTE P0.5 – TVB-3 №2; PPNTE P1 – TVB-3 №39, PPNTE P2 – TVB-3 №162, PPNTE P2-1 – TVB-3 №3, PPNTE P4 – TVB-3 №46, PPNTE P8 – TVB-3 №67, PPNTE P16 – TVB-3 №27, PPNTE P32 – TVB-3 №V 24-2.
5. A combination of individual selection, design-technological and structural methods of precision improvement has allowed creating the military secondary standard of voltage unit from 0.1 to 1000 VAC in the frequency range from 10 Hz to 30 MHz VVETU 08-07-01-09.

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