THE 0.1 V TO 1000 V ALTERNATE VOLTAGE STANDARD IN THE FREQUENCY RANGE FROM 10 Hz TO 30 MHz

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Abstract: In a given summary the alternate voltage standard, which works over the voltage range from 0,1 V to 1000 V and the frequency range from 10 Hz to 30 MHz is presented. In the paper its structure and the main scientific and technical advancements are considered.

Key words: the alternate voltage standard, the automation system, the thermal voltage converter, the voltage wideband amplifier

1. INTRODUCTION

An alternate voltage standard is one of the most difficult standards, because there is no such physical phenomenon which would reproduce the root-mean-square (RMS) of variable voltage of the set value. Instead there is a definition of the periodic voltage RMS:

$$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u^2(t)dt}\ , \qquad (1)$$

where T – is a voltage period; $u(t)$ – current voltage value.

In this connection there are several approaches in defining the voltage RMS.

In all cases in that or the other method the dependence (1) is realized.

This formula can be realized by several methods.

The first one is based on measuring the instantaneous values with the following digital processing to calculate the U_{RMS} value by its definition. But the given method has limitations over the frequency range.

The second method, is based on an amplitude detection of a pure sine voltage by one or several instantaneous values. The necessary condition of a high accuracy is the extraordinarily great requirements to "sine" voltage shape.

The third one is based on equality of thermal effects of direct and alternate voltage on the same thermo-electrical converter.

In all cases the AC voltage root-mean-square value is determined through a DC voltage value, which is passed from sources, based on fundamental physical (Jefferson) or chemical (Winston) regularities.

The world's most prevalent method is the comparison of thermal effects of alternating and direct currents voltages. This method has been named thermo-comparison and is used in the national standards of most of the countries, including: the United States of America, Germany, Russia, Holland, England, Austria, Switzerland, Ukraine.

There is no fundamental difference between the national standards based on thermo-comparison of DC and AC voltages. The difference of countries' national standards lies in a justification of reproduction errors of AC voltage RMS value.

For the standards of thermo-comparison type the main errors sources are the following:

1) a DC-AC voltage transfer error, which is conditioned by the fundamental Thomson and Peltier phenomena. They create an additional heat except for the Joule heat, determined by the square of voltage RMS value in accordance with the formula (1);
2) frequency error, conditioned by the presence of reactive resistance components both in thermoelectric converters and in additional resistances, joint members, switches, etc.
3) an error caused by nonsimultaneous comparison;
4) a reproduction error of DC voltage, which is used as a passed unit of RMS value;
5) a composed error of the others apparatus set components, by means of which the transmission of unit from DC to AC voltage is realized.

As far as by the definition a standard of physical unit has the best metrology specifications, there are no other devices or systems for an attestation of a standard. The attestation is carried out with the help of a theoretical-experimental method.

This method is based on creation of a model and assessment of its quantitative indexes.

The basic unit of the alternate voltage standard of a thermo-comparison type is a standard Thermoelectric Voltage Converter (TVC). There are a few physical processes of TVCs, each of which influences the metrology characteristics during the reproduction of AC voltage.

2. STRUCTURE AND DESCRIPTION OF ALTERNATE VOLTAGE STANDARD

2.1. Structure and measuring devices

The alternate voltage standard, created in The Research Institute of Experimental Research Automation, represents the automation system which consists of commercial high-precision measuring instruments (multimeter HP3458A, calibrators V1-29 and N4-7, power metre NRVD with NRV-Z51 thermal sensor, nanovoltmeter HP34420A, frequency meter Ch3 64/1, spectrum analyzer NI PXI-1042Q, and attenuator HP8495G) and units designed and manufactured by the Institute (frequency and dynamic range extension unit, measuring unit, 4 sets of thermal voltage converters and commutation switches).

The automation system is controlled by computer via IEEE-488.2 interface bus [1] and RS-232 port with the help of specific software created in the Institute. The program has been developed in Microsoft Visual Studio. NET in C# language and works under Microsoft Windows XP.

Table 1. Random Relative Errors of AC Voltage Standard (in ppm).

Voltage, V	Frequency						
	10 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz	30 MHz
0.5	8.0	2.2	5.1	7.1	24.0	15.0	12.0
1	12.0	4.7	2.7	5.6	21.0	15.0	10.0
2	5.5	2.3	1.7	4.2	19.0	6.0	16.0
4	6.5	2.6	3.5	4.1	19.0	11.0	7.0
8	5.5	3.4	2.4	4.6	21.0	5.0	17.0
16	9.2	6.2	1.5	7.7	24.0	13.0	23.0
32	15.0	13.0	4.1	76.0	27.0	14.0	24.0
50	15.0	6.1	6.0	11.0	28.0	-	-
100	17.0	8.3	6.1	13.0	14.6	-	-
300	21.0	4.2	3.6	37.0	-	-	-
500	28.0	4.0	6.9	38.0	-	-	-
1000	32.0	12.0	12.0	39.0	-	-	-

The reproduction of alternate voltage unit is carried out through its comparison to DC voltage unit of a known value. This comparison is performed with the help of standard thermoelectric voltage converters for the voltages with nominal values of 0.5 V, 1 V, 2 V, 4 V, 8 V, 16 V, 32 V; certified thermoelectric voltage converters for the voltages with nominal values of 50 V, 100 V, 300 V, 500 V, 1000 V; attenuator Hewlett Packard HP8495G, and nanovoltmeter HP34420A applied as thermal-EMF meter. The DC voltage unit used for the reproduction of alternate voltage unit is registered by multimeter HP3458A.

The alternating voltage calibrator V1-29 is used as alternate voltage source in the frequency range of 10 Hz to 100 MHz and voltage range of 0.3 V to 3 V. The universal calibrator N4-7 is used as DC voltage and AC voltage source in the frequency range up to 1 Mhz.

Two-channel nanovoltmeter HP34420A is applied to measure and transfer the thermal EMF values at the outputs of standard and valid thermal voltage converters.

Power meter NRVD is used for the definition of frequency error of reference standard thermal converter in the 30 MHz … 100 MHz frequency range for the further interpolation of its frequency response.

Frequency and dynamic range extension unit contains three built-in amplifier units and is applied for the generation of 30 V voltage within the range of 1 kHz … 30 MHz, 100 V voltage up to 1 MHz frequency, and 1000 V voltage up to 100 kHz frequency.

2.2. The Thermoelectric Voltage Convertors

For the thermoelectric comparison of DC voltage to AC voltage a set of Standard Thermal Voltage Converters (STVC) is used. The STCV are also the standards of collation with the other standards. A STVC consists of a resistor and a TVC (of the ДТПТ- 6 type) connected in series and an additional resistance, mounted in one housing. In order to create an equitemperature environment in the area of electric connections and to protect a converter from the electric and high-frequency electromagnetic fields the housing of every STCV is made of a red copper.

For the minimization of temperature difference of STCV pin connections with an external electric circuit the insulators of STCV leads are made of aluminium nitride. STCVs have the nominal voltage values of 0.5 V, 1 V, 2 V, 4 V, 8 V, 16 V, 32 V. The thick grid of nominal values allows to pass the value of voltage unit from one range to the other without a considerable loss of thermo-EMF. This occurs because of the parallel connection of STCV with the different nominals where the given value of voltage doesn't exceed the nominal of a more sensible STCV. The input current of STCV at the nominal voltage values is 5 mA. At sizeable initial frequency errors their correction is foreseen by a built-in air condenser of variable capacity or experimentally assorted ceramic condenser.

A frequency error for the measuring amendment is given in the description of every STCV. While working with STCV, thermo-dampers are put on from the output clamps sides.

A set of Portable Thermoelectric Voltage Converters (PTVC) is also included into the standard. It is intended for the use in local metrology laboratories. The PTVC structurally coincide with STVC except for that a ТВБ-3 thermal voltage converter is used instead of ДТПТ-6. Frequency characteristics of PTVC are obtained by collation with STVC.

A set of certified thermoelectric voltage convertes is used for thermoelectric comparison of AC voltage to DC voltage. TVCs - 12/2 are also the standards of collation with the other standards. A set of TVC - 12/2 consists of two thermo-heads and five additional resistors for the voltages of 50 V; 100 V in the frequency range up to 1 MHz and 300 V; 500 V; 1000 V in the frequency range up to 100 kHz. A presence of two thermo-heads in the TVC - 12/2 set enables an evaluation of DC-AC voltage transition errors or converters frequency errors from one nominal value to the next one.

The TVC - 12/2 set can be certified on the state standard of Ukraine ДЕТУ 08-07-02 within the possibilities limits of the latter.

The set of portable thermoelectric voltage converters is used for the thermoelectric comparison in the local metrological laboratories. The metrological characteristics of a TVC – 12 are obtained by its collation with the TVC - 12/2.

The set of TVC - 12 has got one thermo-head and five additional resistors for the voltages of 50 V; 100 V in the frequency range up to 1 MHz and 300 V; 500 V; 1000 V in the frequency range up to 100 kHz.

3. THE ESTIMATION OF TVC's ERRORS

3.1. Theoretical bases

In the process of thermo-comparison a useful component is the Joule heat component. An equality of Joule heat at AC and

DC voltage corresponds to an equality of AC and DC voltage root-mean-squares. An ideal TVC model is described by dependence

$$E = K_u U^2 . \quad (2)$$

A real TVC macro-model can be presented by the three basic dependences, which take into account its deviation from the ideal model: additive, multiplicative and exponential.

We use a multiplicative model because of its ease in experimental researches and a step-down to the requirements of setting a given voltage value. We are going to characterize a TVC through the current value of transformation coefficient, namely

$$K_u\left(Ui\right) = \frac{Ei}{Ui^2} . \quad (3)$$

Let us introduce the following concepts:

$K_u^{+}\left(U_i^{+}\right)$ – transmission coefficient at positive input voltage of U_i^{+} value;

$K_u^{-}\left(U_i^{-}\right)$ – transmission coefficient at negative input voltage of U_i^{-} value;

$K_u^{\sim}\left(U_i^{\sim}\right)$ – transmission coefficient at AC voltage of $U_i^{\sim}$ value.

As far as in the sequel we are considering only voltage transducer, we are not applying an index u for simplicity, also we are not denoting a functional dependence of coefficient from voltage, a priori keeping it in mind.

Then let us accept the following notations:

$$K^{+} = \frac{E^{+}}{\left(U^{+}\right)^2},\ K^{-} = \frac{E^{-}}{\left(U^{-}\right)^2},\ K^{\sim} = \frac{E^{\sim}}{\left(U^{\sim}\right)^2}, \quad (4)$$

where E^{+} – is a thermo converter's Electromotive Force (EMF) value at positive voltage U^{+};

E^{-} – TVC's EMF value at negative voltage U^{-};

$E^{\sim}$ – TVC's EMF value at AC voltage $U^{\sim}$;

$U^{+}, U^{-}, U^{\sim}$ – values of positive, negative and alternative voltages.

By TVCs comparison they are by turns connected to the AC and DC voltage source.

In an ideal case the equality of thermo-EMFs when connecting to AC voltage $E^{\sim}$ and DC voltage $E^{=}$ means the equality of AC and DC voltage RMSs, notably, if $E^{\sim} = E^{=}$, then $U^{\sim} = U^{=}$.

Voltages $U^{+}, U^{=}$ are measured by direct voltage measuring means.

An ideal case takes place, when in TVC the Peltier and Thomson effects as well as the frequency error are absent.

In modern single-element vacuum noncontact TVCs (ТВБ) it is possible to ignore a frequency error at middle frequencies (200-2000 Hz). It allows to define a AC-DC voltage transfer error separately at low frequencies and the frequency error at high frequencies. A sum of these two errors gives the AC-DC voltage transfer error.

This error is denoted as δ_{acdc} (ac-dc transfer difference). It can be assessed by an indirect or a direct measuring. Within the indirect measuring E^{+} and E^{-} are used as base values, or K^{+} and K^{-}, within the direct measuring of $K^{\sim}$ (4), K^{+}, K^{-}.

Let us examine both δ_{acdc} estimation methods.

3.2. Indirect Method of δ_{acdc} Estimation

The AC-DC transfer error at middle frequencies is defined by Peltier and Thompson thermoelectric effects. We shall consider their combined influence. Fig. 1 schematically shows the distribution of heater temperature along its body caused by Peltier and Thompson effects. The Joule heat and the leakage of heat through the thermocouple are not taken into consideration on these diagrams.

As far as temperature and EMF are linearly dependent in the first approximation. instead of temperature dependence along the heater, the fig. 1 shows the dependence of EMF $E(l)$ from heater length l and the current I_H flow direction.

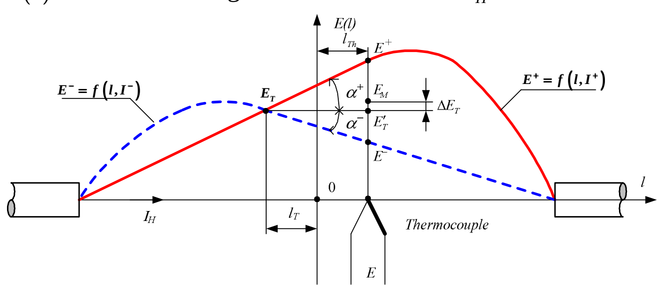

Fig. 1.-Temperature presented by EMF vs Heater length and its current

Taking into account the thermal inertia of the heater at the alternative current, the thermal equilibrium point of Thompson and Peltier effects and the corresponding thermal EMF is located on the crossing of temperature (presented by EMF) distribution curves at positive and negative current directions. If the thermocouple E is located at the curve crossing point, the δ_{acdc} error will be absent at the l_T distance from the heater middle. If the thermocouple is mounted on the heater in the point located at l_{Th} distance from the heater middle, the presence of the δ_{acdc} error becomes obvious even in the case when the positive and the negative currents have the same value, but opposite polarity.

$\overline{E^{-}E_T E^{+}}$ triangle consists of two rectangular triangles $\overline{E_T E'_T E^{+}}$ and $\overline{E_T E'_T E^{-}}$. It is possible to state that

$$E'_T \text{Å}^{-} = \text{Å}_T E'_T \times tg\alpha^{-} , \quad (5)$$

$$E'_T \text{Å}^{+} = \text{Å}_T E' \times tg\alpha^{+} , \quad (6)$$

where α^+, α^- are the angles created by hypotenuses and heights of the said triangles.

The AC-DC transfer error represented by EMF is:

$$\Delta E_T = \left(E^+ - E^-\right)\cdot 0,5\cdot\frac{tg\alpha^+ - tg\alpha^-}{tg\alpha^+ + tg\alpha^-}, \qquad (7)$$

where ΔE_T is the absolute AC-DC transfer error in the EMF dimensions. From the formula it follows that the transfer error is equal to zero in two cases: if ($E^+ - E^- = 0$) or ($tg\alpha^+ - tg\alpha^- = 0$).

If a given permissible voltage transfer error is $\left[\delta^U_{acdc}\right]_{perm}$, then a permissible heteropolarity error $\left[\delta^E_{pol}\right]_{perm}$ can be defined as:

$$\left[\delta^{\AA}_{pol}\right]_{perm} = 4\frac{tg\alpha^+ + tg\alpha^-}{tg\alpha^+ - tg\alpha^-}\left[\delta^U_{acdc}\right]_{perm}. \qquad (8)$$

Taking into consideration that

$$-1 < \frac{tg\alpha^+ - tg\alpha^-}{tg\alpha^+ + tg\alpha^-} < 1, \qquad (9)$$

the permissible heteropolarity error must not even in the worst case exceed the value of permissible voltage transfer error multiplied by 4, i.e.:

$$\left|\left[\delta^E_{pol}\right]_{perm}\right| < 4\left|\left[\delta^U_{acdc}\right]_{perm}\right|. \qquad (10)$$

If in the requirements specification a non-excluded systematic error is 10 ppm, the permissible heteropolarity error then must not exceed 40 ppm, if all of the other components of non-excluded systematic error are absent.

If maximal errors of DC measurement by the multimeter HP3458A and the nanovoltmeter HP34420A do not exceed 10 ppm each, then with some reserve the component of non-excluded systematic error caused by TVC heteropolarity must not exceed a half of the permissible error, i.e.:

$$\left|\left[\delta^E_{pol}\right]_{perm}\right| < 40{,}1 \text{ ppm}. \qquad (11)$$

In TVC-6 the permissible heteropolarity error has a limit of 1000ppm. A transfer error by thermo-comparison has a limit of 100ppm. Notably a meaning of an influence coefficient equal to 0,1 is assumed. That is why while choosing TVCs for the standard, it is necessary to choose the ones with permissible EMF heteropolarity error less than 100 ppm.

3.3. Direct Method of Transfer Errors δ_{acdc} Estimation at Middle Frequencies

The direct method of δ_{acdc} estimation is possible if there is an AC voltage source with the precisely defined value, or an AC voltage source with its RMS value rigidly bound to the value of some DC voltage, which is supplied to a TVC with a by-turn polarity change.

If a precision AC and DC voltmeter is available, the AC-DC transfer error δ_{acdc} can be defined by the formula:

$$\delta_{acdc} = \frac{U^{\sim}}{U^{=}} - 1 = \frac{N^{\sim}\left(1+\delta_{ac}\right)}{N^{=}\left(1+\delta_{dc}\right)} - 1, \qquad (12)$$

where $N^{\sim}$ – are AC voltmeter meterage;

δ_{ac} – AC voltage measuring error;

$N^{=}$ – DC voltmeter meterage by mesuring a half-sum of positive and negative voltages when a null-comparison condition ($E^{\sim} = E^+ = E^-$) is true;

δ_{dc} – DC voltage $U^{=} = \dfrac{\left|U^+\right| + \left|U^-\right|}{2}$ measuring error.

When $\delta_{ac} << 1$

$$\delta_{acdc} \approx \frac{N^{\sim}}{N^{=}}\left(1+\delta_{ac}+\delta_{dc}\right) - 1. \qquad (13)$$

3.4. Frequency Error

The frequency error of STVCs is defined by their design, the reactivities of used TVCs and additional resistor.

We have developed a special STVCs, the inductance of which is reduced through the shortening of direct and reverse current wires general length and the configuration is approaching to a bifilar one.

The frequency characteristics of the reference STVC is calculated by the results of reactive elements direct measurements.

In order to minimize the frequency error generally a frequency error of STCV with any nominal voltage value is defined through a frequency error of STCV with the nominal of 2 V.

There has been developed a multiplicative algorithm for the definition of frequency errors' difference for two STVCs, which are connected in parallel with the adjustment of the given voltage value for the reference STVC at the calibration frequency of 1 KHz. The frequency error difference is defined by the following formula:

$$\gamma_{test}(f_i) - \gamma_{ref}(f_i) = = 0,5\left[\frac{E_{ref}(f_c)}{E_{test}(f_c)}\cdot\frac{E_{test}(f_i)}{E_{ref}(f_i)} - 1\right]\cdot 10^6 \ ppm, \qquad (14)$$

where f_i – is the frequency, at which the frequency error is assessed;

f_c – calibration frequency (1 KHz mostly);

$\gamma_{ref}(f_i)$ – the frequency error of the Reference STVC (RSTVC). This error is calculated or experimentally obtained with the help of the more precise measuring instrument;

$\gamma_{test}(f_i)$ – the frequency error of the tested STVC;

$E_{ref}(f_c)$, $E_{test}(f_c)$ – thermo-EMFs of the reference and tested STVCs at the calibration frequency f_c;

$E_{ref}(f_i)$, $E_{test}(f_i)$ – thermo-EMFs of the reference and tested STVCs at the f_i frequency.

The formula (14) defines the error of the tested STVC with a glance to the supplied voltage and the error of the previously certified STVC, which is regarded as a reference converter.

Considering a narrow range of a TVC it's only possible to certificate a whole STVC set making a chained measuring procedure and taking into account errors of STVC with neighbor and overlapping ranges.

3.5. Error Caused by the nonsimultaneous comparison

The thermal comparison procedure supposes the turn-by-turn connection of STVC to the AC voltage, positive DC voltage, and negative DC voltage.

The change of calibrator modes and the switching of commutation relays cannot be immediate. To avoid the errors of transient processes, it is important to define the duration of commutations, and the start time of integration.

The transient processes are caused by the interruptions of input signals while commutation, and also by certain non-equality of the voltages that are turn-by-turn connected to the converter.

Theoretically, the time of input signal assertion is instant. But when this time is too long, the error increases because of the non-stability of signal sources, measuring instruments, and STVC itself. That is why we have investigated the dependence of error from the time of voltage-converter commutation from the transient process point of view. In the first approximation, the STVC is a single-mess low frequency filter with the thermo-converters time constant of 1-5s.

On this assumption, while realizing the measuring algorithm, the commutation time for one voltage is 30 s. with the duration of one pair of measurements of 3 s. The last 4 measurement before the commutation are averaged and used for estimations. Then the averaging of five measurement cycles is done. This double averaged value is used for the calculations.

Besides, by each measurement it is recommended to warm-up the equipment for 30 min.

3.6. DC Voltage Measuring Error

The most precise measuring instruments used for AC voltage standard are the multimeter HP3458A and the two-channel nanovoltmeter HP34420A.

The multimeter HP3458A presents the measurement result with 8S digits at measurement ranges 0.1, 1, 10, 100, and 1000 V. It is applied for the measurement of the STVC input DC voltage and for the power frequency.

The nanovoltmeter HP34420A presents the measurement result with 7S digits, and is equipped with two channels: from 1 mV to 10 V and from 10 mV to 100 V.

Considering the specification of these measuring instruments, the 2 V voltage, measured by the multimeter HP3458A, can be represented with the resolution of 1 nV, and the 1 mV voltage, measured by the nanovoltmeter HP34420A, can be presented with the resolution of 100 pV.

In this way it is possible to neglect the resolution error of these measuring instruments in our task. The limit of one-year usage error of HP3458A does not exceed 10 ppm, what makes 0,2 of the least permissible error of voltage unit transfer.

4. MAIN ACHIVEMENTS

The main scientific and technical achievements in the alternate voltage standard are the following:

– The mechanism of AC-DC transfer errors caused by Thompson and Peltier effects has been investigated. As a result, more severe restrictions were introduced for the individual selection of thermal voltage converters. For compensation of these errors a computational method, based on the parallel and series connection of thermal converters, has been proposed. Thus, during the experimental validation, the percentage of acceptable converters out of a whole set has been increased.

– The methodology of converters' stability estimation over the observation period has been developed with the help of the designed automation system for the research of converters' short-time instability histogram.

– The interpolation algorithm for the alternate voltage reproduction has been proposed. This has quickened the measurement process, in connection with reversal of zero thermal comparison method.

– The new evaluation formula of errors difference for the standard and valid converters has been deduced. It allowed to lower stability requirements of signal sources and accelerated obtaining results.

– The iteration algorithm of digital stabilization with the wide range of the output voltages of alternate and DC voltage sources has been created and introduced, which provides the rapid setting of the desired value level and reduces the accuracy requirements to the voltage sources (calibrators and amplifiers)

– thermal comparison transients have been investigated, that allowed to optimise a integration time of and temporal instability of a measuring channel.

– The design theory for wide-range high-voltage amplifiers has been developed and implemented, that allowed to achieve the signal slew rates up to 10000 V/µs at the output voltage of 30 V at 30 MHz frequency, 1000 V/µs at the output voltage of 100 V at 1 MHz frequency, and 1000 V at 100 kHz frequency. Such slew rates were achieved for the first time in world practice. Due to this fact, the technical specifications of the alternating voltage standard in voltage-and-frequency ranges exceed the specifications of existing world standards known to us.

– The algorithms of measuring and interaction of measuring devices with different interfaces has been developed and realized, which allowed to create the fully automated system for the registering data measurement and the calculation of final results including their statistical processing. In its turn, the automation system provides the complete objectivity of measuring results, and appreciably accelerates the calibration. The function of an operator is reduced to the connection and calibration of the necessary measuring devices, to the input of commands for the involved devices and the supervision of alternate voltage standard operation flow [2].

– The usage of HP8495G attenuator allows to reproduce alternate voltages from 0.001 V in the frequency range up to 100 MHz.

– The Patent of Ukraine is received for the transformation method of purely sine voltage during a time interval. This method is used in the measuring unit. Which allowed implementing the direct determination method of the AC-DC transfer error.

5. LEADING-OUTS

The 0,1 V to 1000 V alternate voltage standard in the frequency range of 10 Hz to 30 MHz passed all the research stages and tests, including state verification. It is calendared in the State Register of Primary and Secondary Standards of Ukraine under the BBETY 08-07-01-09 number.

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