VOL. 20, NO. 3, FEBRUARY 2025 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

CONSTRUCTION AND RESEARCH OF CHARACTERISTICS OF THE HIGH VOLTAGE DIRECT CURRENT STANDARD

Oleh Velychko and Ruslan Vendychanskyi
Institute of Electromagnetic Measurements, State Enterprise "Ukrmetrteststandard", Kyiv, Ukraine
E-Mail: velychko@hotmail.com

ABSTRACT

High voltage (HV) power transmission is standard practice in modern power engineering due to its numerous advantages, the main of which is the reduction of energy losses and increased transmission efficiency. HV direct current (DC) transmission lines allow the transmission of electricity over long distances with greater power and lower losses than HV alternating current transmission lines. Accurate voltage measurement is necessary for monitoring and controlling HVDC lines to avoid overloads and equipment damage. Voltage measuring transformers, resistive and capacitive voltage dividers; electrostatic voltmeters, digital voltmeters with special converters are used to measure HVDC. National standards and working standards have been created to calibrate such HVDC measuring instruments. Research the metrological characteristic of the national standard of HVDC is necessary to continuously maintain metrological traceability of HVDC measurements on a national level. Technical and metrological characteristics have been established for the constructed HVDC standard and its main components. These characteristics are regularly researched using specially developed methodology. This methodology examines the low voltage blocks and the compiled measure of stationary and mobile parts of the HVDC standard. The results of the research of compiled measures and low-voltage blocks of the stationary part of the HVDC standard confirm the correctness and stability of the established characteristics of the standard. Deviation of actual value of voltage of compiled measure from the nominal value of 1,000 V does not exceed ±1.3 V (0.13%). The long-time instability of actual voltage of compiled measures of 10,000 V does not exceed ±0.13 V (0.013%). The obtained values of the main metrological characteristics of the standard are confirmed by the results of international comparisons of similar national standards. This ensures metrological traceability of HVDC measurements at the national level.

Keywords: high voltage, direct current, measurement, calibration, measurement standard.

Manuscript Received 14 January 2025; Revised 1 February 2025; Published 21 March 2025

1. INTRODUCTION

Modern power engineering ensures the functioning of industry, transport, construction, and other sectors of the economy, the stability of energy supply in conditions of growing demand. It contributes to the development of production, the spread of electric vehicles, smart homes, etc., and is focused on diversifying energy sources to reduce dependence on limited resources such as fossil fuels. The use of artificial intelligence, smart grids and energy storage systems improves the efficiency and reliability of energy systems.

High voltage (HV) power transmission is standard practice in modern power engineering due to its numerous advantages, the main of which is the reduction of energy losses and increased transmission efficiency. HV minimize losses and allow the transmission of electricity over long distances. HV power transmission requires the use of transformers, which step up the voltage for transmission and step down before delivery to end users. This ensures the flexibility and security of power systems. HV direct current (DC) transmission lines allow the transmission of electricity over long distances with greater power and lower losses than HV alternating current (AC) transmission lines [1, 2].

HVDC measurement is important for many industries, including energy, electronics, and research. This allows for the integration of new energy sources (offshore wind farms, solar power plants, etc.), the development of infrastructure, and the improvement of technologies. Accurate voltage measurement is necessary for monitoring and controlling HVDC lines to avoid overloads and equipment damage. In laboratories, HVDC measurements are used to test insulating materials, power and instrument transformers, cables, and other components.

2. LITERATURE REVIEW

Specialized instruments are used to measure HVDC, which provide the necessary measurement accuracy. Such measuring instruments include: voltage measuring transformers; resistive and capacitive voltage dividers; electrostatic voltmeters; digital voltmeters with special converters, etc. National standards and working standards have been created to calibrate such HVDC measuring instruments. Metrological traceability of HVDC measurements is ensured by national standards of HV units. Research into national standards of HV units is a rather complex scientific and technical task, as solved by specialized national laboratories.

The basic principles and characteristics of HVDC transformers and the key problems of resistive-capacitive voltage dividers in practical applications are analyzed in

ARPN Journal of Engineering and Applied Sciences

[3]. The use of resistive and capacitive voltage dividers for voltage measurement in HVDC systems due to their advantages is defined in [4]. The methodology for measuring phase-separated partial discharges in HVDC systems with DC voltage containing AC harmonics or DC voltage ripples is presented in [5]. The method for full coverage of the HVDC system in a limited voltage range and the calibration method in the voltage range of 800 kV and above using a scale factor are analyzed in [6]. A combined HVDC measurement method suitable for the protection and control of smart grids is proposed in [7]. National measurement standards of HVDC have different designs and metrological characteristics. Research into their characteristics is an urgent task.

3. MATERIALS AND METHODS

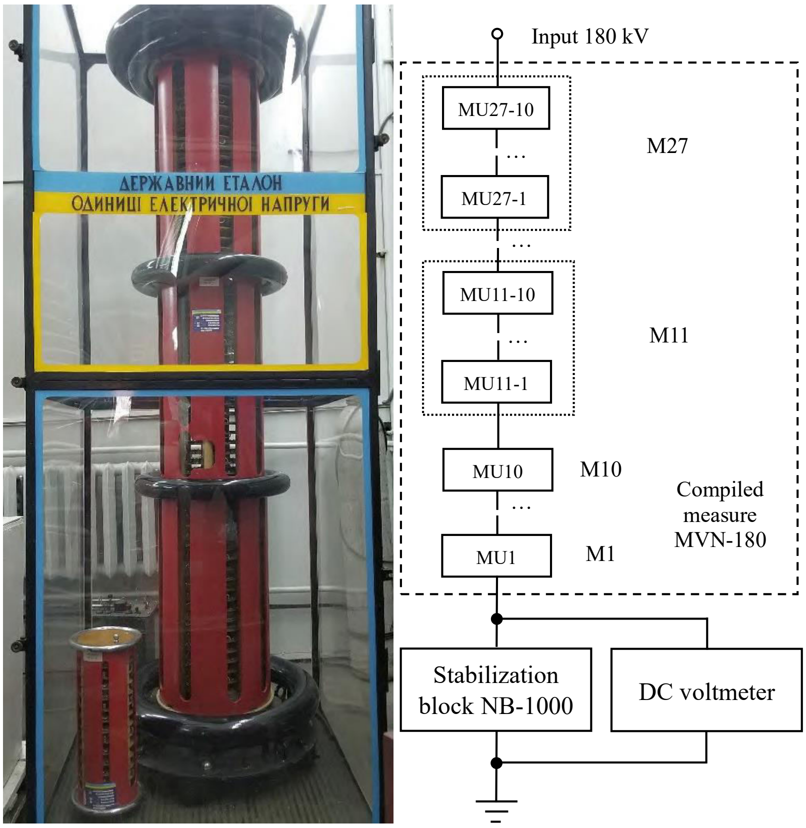
3.1 National Standard of the HVDC Units

The National Standard of the HVDC units in the range from 1 kV to 180 kV (HVDC Standard) was created and is stored at the State Enterprise "Ukrmetrteststandard" (UMTS, Kyiv, Ukraine) [8]. National standards of the HVDC of different national laboratories provide the highest level of calibration of HVDC working standards for accredited calibration laboratories according to the requirements of the international standard ISO/IEC 17025 [9]. They provide the lowest uncertainty of HVDC measurements, as assessed by the requirements of the guides [10, 11]. The HVDC Standard provides metrological traceability of HVDC measurements on national level with an expanded measurement uncertainty of 3.6･10-4 [12]. The HVDC reproduction step of the standard is 1 kV in the range from 10 kV to 180 kV. Its annual instability of the standard does not exceed 3･10-4. The results of the HVDC Standard instability research are given in [13]. For estimation of the drift of the standard were used [14, 15]. The calibration and measurement capabilities of the standard are published in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM) [16]. The HVDC Standard participated in international comparisons of national standards of HVDC in the voltage range from 1 kV to 100 kV at a nominal current of 5 mA [17].

HVDC Standard consists of stationary and mobile parts. The stationary part of this standard is located in a special laboratory of the UMTS (Figures-1, (a)) and consists of compiled measure of 180 kV DC (MVN-180), a device for stabilizing the operating current of HVDC (NB-1000) (Figures-1, (b)), and a precision DC voltmeter. The mobile part of the standard consists of a compiled measure of 10 kV DC (MVN-10), a device for stabilizing the operating current of HVDC (NB-100), and a precision DC voltmeter. Compiled measures MVN-10 and MVN-180 are built on single-value DC voltage measures of two types, which include Zener diodes. Single-value measures of the first type have a nominal voltage of 1 kV (M1…M10), and of the second type - 10 kV (M11…M27). The purpose of stabilizing the operating current of both parts of the standard is to ensure stabilization of the DC flow through the corresponding compiled measures at the level of 5 mA ± 5 µA.

VOL. 20, NO. 3, FEBRUARY 2025 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com



(a) (b)

Figure-1. General view (a) and structural diagram (b) of stationary part of the HVDC Standard.

3.2 Research of Low Voltage Blocks of the HVDC Standard

The main factors affecting the stability of the stabilization current of low-voltage units are the operating voltage range and the time of continuous operation. To identify the influence of these factors on the metrological characteristics of low-voltage blocks NB-100 (Figure-2) and NB-1000 (Figure-3), the following research must be conducted in the operating voltage range:

- determine the deviation of the actual values of the stabilization current from the nominal value;
- determine the changes in the actual value of the stabilization current;
- determine the deviation of the actual value of the stabilization current from the nominal value after 4 hours of continuous operation of the low-voltage blocks NB-100 and NB-1000.

The deviation of the actual value of the stabilization current I of the low-voltage blocks NB-100 or NB-1000 from the nominal value ΔI_n was determined by the equation:

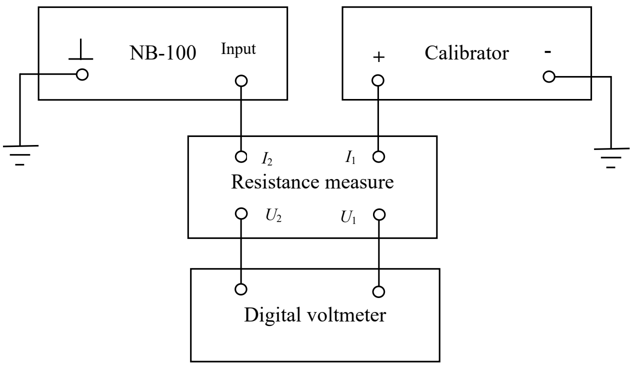


Figure-2. Structural diagram for research of low voltage block NB-100.

ARPN Journal of Engineering and Applied Sciences

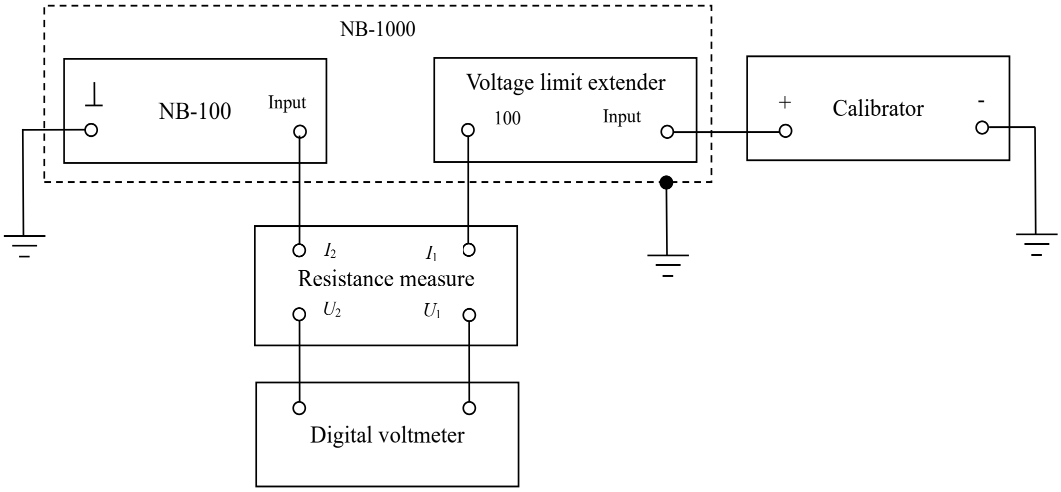


Figure-3. Structural diagram for research of low voltage block NB-1000.

$$\Delta I_n = U_a / R - I_n, \tag{1}$$

where U_a is the actual voltage value measured by a digital voltmeter; R is the nominal resistance value of the electrical resistance measure type of P331 (1000 Ohm); I_n is the nominal value of the stabilization current (5.0 mA). The change in the actual value of the stabilization current ΔI_s is determined by the equations:

$$\Delta I_s = I_{100} - I_{10} \quad \text{for NB-100,} \tag{2}$$

$$\Delta I_s = I_{1000} - I_{100} \quad \text{for NB-1000,} \tag{3}$$

where I_{10} is the value of the stabilization current at a voltage of 10 V; I_{100} is the value of the stabilization current at a voltage of 100 V; I_{1000} is the value of the stabilization current at a voltage of 1000 V.

Determination of the deviation of the actual value of the current from the nominal value after 4 hours of continuous operation of the low-voltage blocks. ΔI_t is determined by the equation:

$$\Delta I_t = U_t / R - I_n, \tag{4}$$

where U_t is the actual voltage value on the electrical resistance measure type of P331 after 4 hours of continuous operation of the NB-100 or NB-1000, determined by a digital DC voltmeter.

3.3 Research of Compiled Measure of Stationary Part of the HVDC Standard

The determination of the average voltage value of each single-value measure of the first type and the voltage of the sections of single-value measures of the second type U_m, which are part of the compiled measure, is carried out regularly. The structural diagram shown in Figure-4 is used for this purpose.

The calculation of the difference of actual voltage value of each i-th unique measure ΔU_{mi} was carried out using the equation:

$$\Delta U_{mi} = U_c - U_{ij}, \tag{5}$$

where U_c is DC voltage set by the calibrator (1007 V); U_{ij} is measured DC voltage by a voltmeter for i-th single-value measure for the j-th observation.

The calculation of the average true voltage value of each single-value measure was performed using the equation:

$$\overline{U}_{mi} = \sum_{j=1}^{n} U_{ij}, \tag{6}$$

where n = 10 is the number of observations.

The calculation of the actual value of the compiled measure voltage U_{cm} was performed using the equation:

$$\overline{U}_{cm} = \sum_{i=1}^{N} \overline{U}_{mi}, \tag{7}$$

where N is the number of single-valued measures included in the compiled measure.

The calculation of deviation of actual voltage value of each compiled measure from its nominal value ΔU_{cm} was performed using the equation:

$$\Delta U_{cm} = U_{cmn} - U_{cm}, \tag{8}$$

where U_{cmn} is the nominal voltage value of the compiled measure.

The determination of the instability in time of the actual value of the voltage of the compiled measures for the period between the last three consecutive determinations of the actual value of voltage of the compiled measures was performed according to the equations:

$$\Delta U_{1cm} = U_{2023} - U_{2024}, \tag{9}$$

$$\Delta U_{2cm} = U_{2022} - U_{2023}, \tag{10}$$

$$\Delta U_{3cm} = U_{2021} - U_{2022}, \tag{11}$$

where ΔU_{1cm}, ΔU_{1cm} and ΔU_{1cm} are the voltage differences of the actual voltage value of each compiled measure, determined for the period 2023-2024, 2022-2023, 2021-2022, respectively; U_{2021}, U_{2022}, U_{2023} and U_{2024} are actual voltage values of each complied measure, determined in 2021, 2022, 2023, and 2024 years, respectively.

4. RESULTS AND DISCUSSIONS

4.1 Results of Research of Low Voltage Blocks of the HVDC Standard

The research of low-voltage blocks is carried out according to the methodology set out in section 3.2.
Results of research of low voltage blocks NB-100 and NB-1000 of the HVDC Standard are shown in Table-1 and Table 2, respectively. In the tables, U is the voltage value at the calibrator output.

Table-1. Results of low voltage blocks NB-100.

***U*, V**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
U_a, V	4.9996	4.9997	4.9998	5.0000	5.0000	5.0001	5.0003	5.0006	5.0009	5.0014
I, mA	4.9996	4.9997	4.9998	5.0000	5.0000	5.0001	5.0003	5.0006	5.0009	5.0014
ΔI_n, μA	-0.4	-0.3	-0.2	0.0	0.0	0.1	0.3	0.6	0.9	1.4
U_t, V	5.0011	5.0013	5.0014	5.0015	5.0016	5.0017	5.0019	5.0021	5.0025	5.0029
I_t, мA	5.0011	5.0013	5.0014	5.0015	5.0016	5.0017	5.0019	5.0021	5.0025	5.0029
ΔI_t, μA	1.1	1.3	1.4	1.5	1.6	1.7	1.9	2.1	2.5	2.9

Table-2. Results of low voltage blocks NB-1000.

U, V	100	200	300	400	500	600	700	800	900	1000
U_a, V	4.9999	5.0000	5.0000	5.0000	5.0002	5.0002	5.0002	5.0003	5.0003	5.0003
I, mA	4.9999	5.0000	5.0000	5.0000	5.0002	5.0002	5.0002	5.0003	5.0003	5.0003
ΔI_n, μA	-0.1	0.0	0.0	0.0	0.2	0.2	0.2	0.3	0.3	0.3
U_t, V	5.0035	5.0035	5.0034	5.0034	5.0036	5.0036	5.0037	5.0037	5.0038	5.0039
I_t, мA	5.0035	5.0035	5.0034	5.0034	5.0036	5.0036	5.0037	5.0037	5.0038	5.0039
ΔI_t, μA	3.5	3.5	3.4	3.4	3.6	3.6	3.7	3.7	3.8	3.9

The deviation of the actual value of the stabilization current from the nominal value for NB-100 does not exceed 1.4 μA. The change in the actual value of the stabilization current in the operating voltage range does not exceed 1.8 μA. The deviation of the actual value of the stabilization current from the nominal value after 4 hours of continuous operation of the NB-100 exceeds 2.9 μA. All the obtained results of the study of the NB-100 meet the established requirements for the standard.

The deviation of the actual value of the stabilization current from the nominal value for NB-1000 does not exceed 0.3 μA. The change in the actual value of the stabilization current in the operating voltage range does not exceed 0.4 μA. The deviation of the actual value of the stabilization current from the nominal value after 4 hours of continuous operation of the NB-100 low-voltage unit exceeds 3.9 μA. All the obtained results of the study of the low-voltage unit NB-100 meet the established requirements for the standard.

The dependence of the deviation of the actual value of the stabilization current from the nominal value after 4 hours of continuous operation of the NB-100 is presented in Figure-4. The same figure shows the dependence of the deviation of the actual value of the stabilization current from the nominal value at the beginning of the operation of the NB-100 for comparison. During continuous operation of the NB-100, the deviation of the stabilization current from the nominal value increases, which can be explained by self-heating and fluctuations in the electrical parameters of the NB-100 elements. The deviation of the actual value of the stabilization current after 4 hours of continuous operation of the NB-100 from the actual value of the stabilization current recorded at the beginning of the research does not exceed 1.6 μA.

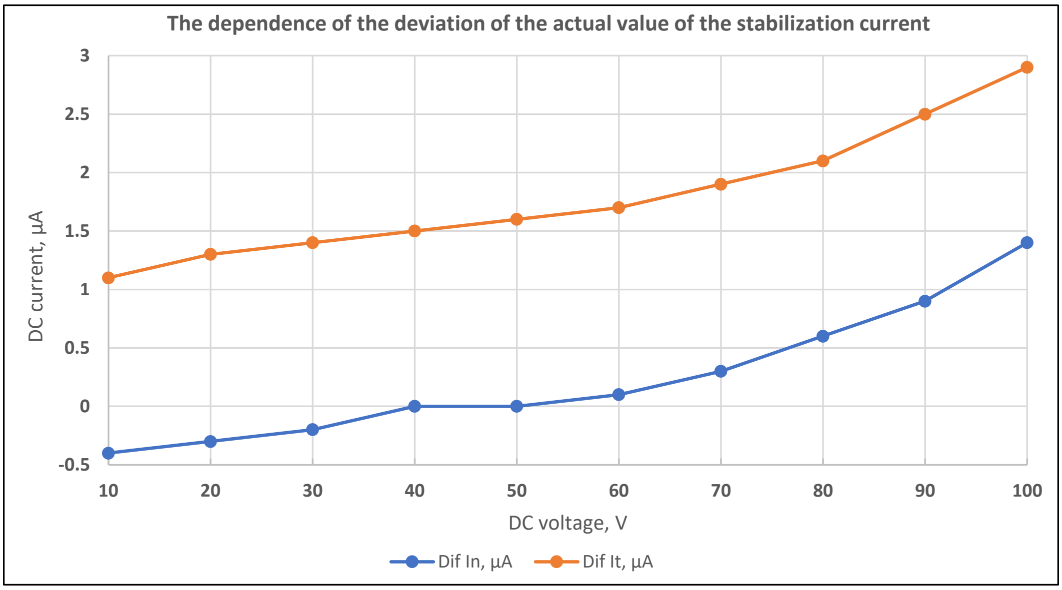


Figure-4. The dependence of the deviation of the actual value of stabilization current from the nominal value of low voltage block NB-100.

The dependence of the deviation of the actual value of the stabilization current from the nominal value after 4 hours of continuous operation of the NB-1000 and deviation of the actual value of the stabilization current from the nominal value at the beginning of the operation of the NB-100 is presented in Figure-5. The deviation of the actual value of the stabilization current after 4 hours of continuous operation of the NB-1000 from the actual value of the stabilization current recorded at the beginning of the research does not exceed 3.3 μA.

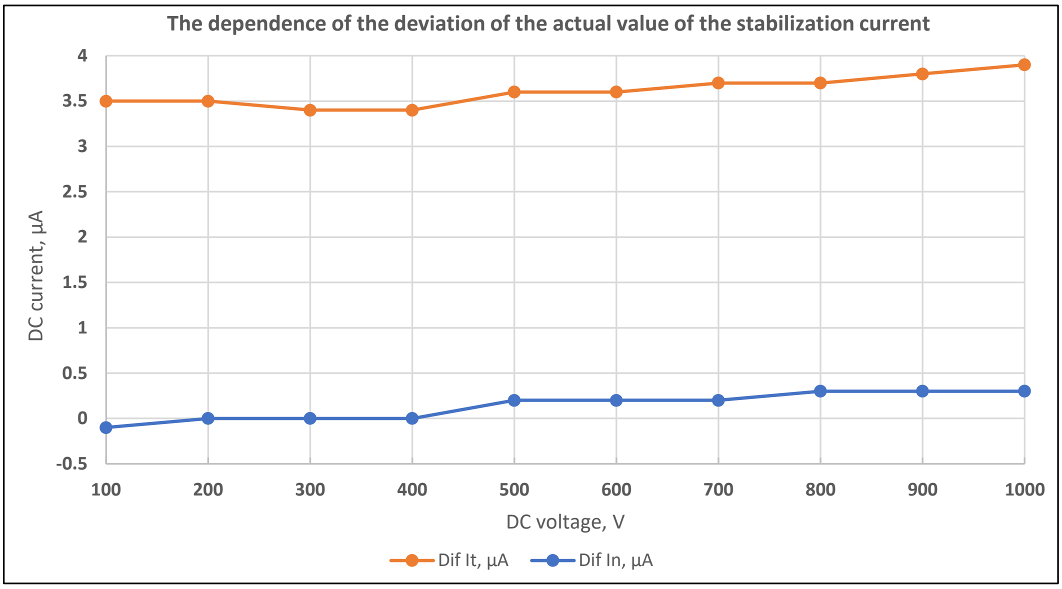


Figure-5. The dependence of the deviation of the actual value of stabilization current from the nominal value of low voltage block NB-1000.

ARPN Journal of Engineering and Applied Sciences

4.2 Results of Research of Compiled Measure of Stationary Part of the HVDC Standard

The research of the compiled measure of stationary part is carried out according to the methodology set out in section 3.3.

Results of measurement of ΔU_{mi} are given in Table-3, and calculation of actual value of the compiled measure voltage U_{cm} are given in Table-4 for measures M1…M10. Results of calculation of actual value of the compiled measure voltage U_{cm} are given in table 5, for example, for measure M11. The maximum voltage deviation of the M1...M10 measures was from -0.033% to 0.002% of the nominal value of 1,000 V, and the maximum voltage deviation of the M11-1...M11-10 measures was from -0.166% to 0.245% of the nominal value of 1,000 V. All these values do not exceed the permissible limit values for the standard.

Table-3. Results of measurement of ΔU_{mi}.

Mea-sure	DC voltage measured by a voltmeter of *i*-th observation, ΔU_{mi}, V										Averag e
	1	2	3	4	5	6	7	8	9	10	
M1	7.1763	7.1753	7.1751	7.1746	7.1742	7.1735	7.1724	7.1732	7.1730	7.1726	7.1740
M2	7.1279	7.1255	7.1250	7.1230	7.1215	7.1204	7.1190	7.1176	7.1170	7.1159	7.1213
M3	7.1695	7.1686	7.1672	7.1658	7.1648	7.1635	7.1628	7.1618	7.1603	7.1586	7.1643
M4	7.1387	7.1378	7.1373	7.1367	7.1359	7.1356	7.1348	7.1337	7.1335	7.1324	7.1356
M5	7.0825	7.0823	7.0805	7.0797	7.0786	7.0771	7.0765	7.0752	7.0738	7.073	7.0779
M6	7.1344	7.1339	7.1335	7.1330	7.1324	7.1323	7.1318	7.1312	7.1313	7.1310	7.1325
M7	7.1560	7.1556	7.1539	7.1535	7.1526	7.1520	7.1508	7.1510	7.1505	7.1497	7.1526
M8	7.1357	7.1354	7.1343	7.1332	7.1336	7.1325	7.1315	7.1312	7.1301	7.1301	7.1328
M9	7.1290	7.1259	7.1253	7.1261	7.1251	7.1233	7.1228	7.1211	7.1207	7.1203	7.1240
M10	6.9827	6.9808	6.9799	6.9794	6.9787	6.9781	6.9777	6.9764	6.9765	6.9757	6.9786

Table-4. Results of measurement of U_{mi} for measures M1…M10.

Mea-sure	Actual value of DC voltage of *i*-th observation, U_{mi}, V										Averag e
	1	2	3	4	5	6	7	8	9	10	
M1	999.824	999.825	999.825	999.825	999.826	999.827	999.828	999.827	999.827	999.827	999.826
M2	999.872	999.875	999.875	999.877	999.879	999.880	999.881	999.882	999.883	999.884	999.879
M3	999.831	999.831	999.833	999.834	999.835	999.837	999.837	999.838	999.840	999.841	999.836
M4	999.861	999.862	999.863	999.863	999.864	999.864	999.865	999.866	999.867	999.868	999.864
M5	999.918	999.918	999.920	999.920	999.921	999.923	999.924	999.925	999.926	999.927	999.922
M6	999.866	999.866	999.867	999.867	999.868	999.868	999.868	999.869	999.869	999.869	999.868
M7	999.844	999.844	999.846	999.847	999.847	999.848	999.849	999.849	999.850	999.850	999.847
M8	999.864	999.865	999.866	999.867	999.866	999.868	999.869	999.869	999.870	999.870	999.670
M9	999.871	999.874	999.875	999.874	999.875	999.877	999.877	999.879	999.879	999.880	999.876
M10	1000.02	1000.02	1000.02	1000.02	1000.02	1000.02	1000.02	1000.02	1000.02	1000.02	1000.02

Table-5. Results of measurement of U_{mi} for measures M11.

Mea-sure	Actual value of DC voltage of *i*-th observation, U_{mi}, V										Average
	1	2	3	4	5	6	7	8	9	10	
M11-1	1000.176	1000.175	1000.174	1000.172	1000.170	1000.170	1000.168	1000.168	1000.166	1000.165	1000.170
M11-2	1000.220	1000.218	1000.215	1000.214	1000.212	1000.211	1000.210	1000.208	1000.206	1000.204	1000.212
M11-3	999.704	999.702	999.700	999.698	999.697	999.695	999.694	999.694	999.692	999.691	999.697
M11-4	998.979	998.978	998.977	998.976	998.975	998.973	998.973	998.971	998.970	998.968	998.974
M11-5	1001.447	1001.446	1001.445	1001.445	1001.441	1001.441	1001.441	1001.439	1001.439	1001.438	1001.442
M11-6	999.114	999.113	999.111	999.110	999.108	999.107	999.106	999.106	999.105	999.104	999.108
M11-7	1002.452	1002.452	1002.451	1002.451	1002.450	1002.450	1002.449	1002.449	1002.448	1002.448	1002.450
M11-8	998.711	998.709	998.707	998.706	998.706	998.704	998.704	998.703	998.702	998.701	998.705
M11-9	1001.680	1001.679	1001.678	1001.677	1001.677	1001.677	1001.676	1001.675	1001.675	1001.674	1001.677
M11-10	998.344	998.344	998.341	998.340	998.339	998.338	998.337	998.336	998.335	998.335	998.339

Results of calculation of deviation of actual voltage value of combination of M1…M10 measure from its nominal measure value are given in Table-6.

Table-6. Results of calculation of deviation of actual voltage value of combination of M1…M10 measure from its nominal value.

Measure	Combination of measures	Nominal value of compiled measure, V	Actual value of voltage of compiled measure, V	Deviation of actual value of voltage of compiled measure from the nominal value, V
M1	M1	1,000	999.826	-0.174
M2	M1+M2	2,000	1,999.705	-0.295
M3	M1+M2+M3	3,000	2,999.540	-0.460
M4	M1+M2+M3+M4	4,000	3,999.405	-0.595
M5	M1+M2+…M5	5,000	4,999.327	-0.673
M6	M1+M2+…M6	6,000	5,999.194	-0.806
M7	M1+M2+…M7	7,000	6,999.042	-0.958
M8	M1+M2+…M8	8,000	7,998.909	-1.091
M9	M1+M2+…M9	9,000	8,998.785	-1.215
M10	M1+M2+…M10	10,000	9,998.807	-1.194

The deviation of the actual voltage value of combination of M1...M10 measures from the nominal measure value of 1,000 V is from -1.215 V to -0.174 V, which does not exceed the permissible limit value set for the standard.

Results of determination of time instability of actual voltage of combination of M1…M10 measures for the period from 2021 to 2024 are given in Table-7. Results of the same determination for M11 measure are given in Table-8.

Table-7. Results of determination of time instability of actual voltage of combination of M1…M10 measures.

Measure	Actual value of voltage U_{2024}, V	Actual value of voltage U_{2023}, V	Actual value of voltage U_{2022}, V	Actual value of voltage U_{2021}, V	Voltage difference ΔU_{1cm}, V	Voltage difference ΔU_{2cm}, V	Voltage difference ΔU_{3cm}, V	Limits of voltage values in time, V
M1	999.826	999.823	999.820	999.827	-0.003	-0.003	0.007	±0.2
M2	1,999.705	1,999.712	1,999.696	1,999.722	0.007	-0.016	0.026	±0.4
M3	2,999.540	2,999.548	2,999.528	2,999.574	0.008	-0.020	0.046	±0.6
M4	3,999.405	3,999.416	3,999.397	3,999.449	0.011	-0.019	0.052	±0.8
M5	4,999.327	4,999.336	4,999.320	4,999.384	0.009	-0.016	0.064	±1.0
M6	5,999.194	5,999.200	5,999.184	5,999.256	0.006	-0.016	0.072	±1.2
M7	6,999.042	6,999.047	6,999.027	6,999.113	0.005	-0.020	0.086	±1.4
M8	7,998.909	7,998.915	7,998.889	7,998.986	0.006	-0.026	0.097	±1.6
M9	8,998.785	8,998.794	8,998.765	8,998.881	0.009	-0.029	0.116	±1.8
M10	9,998.807	9,998.817	9,998.781	9,998.915	0.010	-0.036	0.134	±2.0

Table-8. Results of determination of the time instability of the actual voltage of M11 measure.

Measure	Actual value of voltage U_{2024}, V	Actual value of voltage U_{2023}, V	Actual value of voltage U_{2022}, V	Actual value of voltage U_{2021}, V	Voltage difference ΔU_{1cm}, V	Voltage difference ΔU_{2cm}, V	Voltage difference ΔU_{3cm}, V	Limits of voltage values in time, V
M11-1	1000,170	1000,178	1000,127	1000,128	0,004	-0,051	0,001	±0.2
M11-2	1000,212	1000,212	1000,158	1000,162	0,000	-0,054	0,004	
M11-3	999,697	999,694	999,65	999,653	-0,002	-0,044	0,003	
M11-4	998,974	998,981	998,929	998,933	0,003	-0,052	0,004	
M11-5	1001,442	1001,452	1001,419	1001,421	0,005	-0,033	0,002	
M11-6	999,108	999,118	999,071	999,067	0,005	-0,047	-0,004	
M11-7	1002,450	1002,487	1002,441	1002,476	0,018	-0,046	0,035	
M11-8	998,705	998,720	998,664	998,689	0,007	-0,056	0,025	
M11-9	1001,677	1001,694	1001,647	1001,663	0,008	-0,047	0,016	
M11-10	998,339	998,355	998,290	998,312	0,008	-0,065	0,022	

Limits of permissible values of time instability of actual voltage value of the compiled measures were determined by the equation:

$$\Delta U_{cm\,lim} = \pm 0.0002 U_{cm}. \tag{12}$$

All actual voltage values of the combination of M1…M10 measures and M11 measure obtained in 2021-2024 do not exceed the permissible limits.

5. CONCLUSIONS

The construction of HV equipment is a complex and multifaceted process that requires consideration of physical, material, engineering, and economic factors. Conductors, insulators, and other components of such equipment must meet stringent requirements for strength, thermal conductivity, and corrosion resistance. Overheating may cause damage to the equipment or change its characteristics. Specialized laboratories are needed to test equipment in conditions close to operational ones. Regular monitoring of the characteristics of HV equipment is the basis for its effective operation. Monitoring its characteristics allows you to maintain the set limits of operating parameters. Methods for monitoring the characteristics of HV equipment, accuracy and systematic assessment of the condition of the equipment. Such techniques help assess the condition of equipment components. The results of equipment performance monitoring are always based on actual measurements.

Technical and metrological characteristics have been established for the constructed HVDC standard and its main components. These characteristics are regularly researched using specially developed methodology. This methodology examines the low voltage blocks and the compiled measure of stationary and mobile parts of the HVDC standard. The results of the research of compiled measures and low-voltage blocks of the stationary part of the HVDC standard confirm the correctness and stability of the established characteristics of the standard. Deviation of actual value of voltage of compiled measure from the nominal value of 1,000 V does not exceed ±1.3 V (0.13%). The long-time instability of actual voltage of compiled measures of 10,000 V does not exceed ±0.13 V (0.013%). The obtained values of the main metrological characteristics of the standard are confirmed by the results of international comparisons of similar national standards. This ensures metrological traceability of HVDC measurements at the national level.

REFERENCES

[1] Schon K. 2019. High Voltage Measurement Techniques. Fundamentals, Measuring Instruments, and Measuring Methods. Springer Nature Switzerland AG, p. 466. doi: 10.1007/978-3-030-21770-9_1

[2] Küchler A. 2018 High Voltage Engineering. Fundamentals-Technology-Applications. Springer Vieweg, Berlin, p. 650. doi: 10.1007/978-3-642-11993-4

[3] Y. Zhang, X. Xiao and X. Yan. 2015. Review of research on measurement technologies of DC high voltage, 7th International Conference on Information Technology and Electrical Engineering (ICITEE), Chiang Mai, Thailand, 179-183. doi: 10.1109/ICITEED.2015.7408937

[4] D. Tzelepis *et al*. 2020. Voltage and Current Measuring Technologies for High Voltage Direct Current Supergrids: A Technology Review Identifying the Options for Protection, Fault Location and Automation Applications, in IEEE Access, 8: 203398-203428, doi: 10.1109/ACCESS.2020.3035905

[5] Florkowski M., Kuniewski M., and Zydroń P. 2022 Measurements and Analysis of Partial Discharges at HVDC Voltage with AC Components, Energies, 15(7): 2510. https://doi.org/10.3390/en15072510

[6] Y. Hou, S. Wang. 2022. Research and application of high voltage measurement technology in DC UHV preventive test, Energy Reports, 8: 16, 868-875. https://doi.org/10.1016/j.egyr.2022.12.147

[7] Z. Li *et al*. 2021. Research on a Composite Voltage and Current Measurement Device for HVDC Networks. IEEE Transactions on Industrial Electronics, 68(9): 8930-8941. doi: 10.1109/TIE.2020.3013772

[8] Velychko O., Vendychanskyi R. 2018. Research of the National Primary Standard of the High DC Voltage, Digest of 2018 Conf. on Precision Electromagnetic Measurement. Paris, France, p. 2. doi: 10.1109/CPEM.2018.8500835

[9] ISO/IEC 17025: 2017. General requirements for the competence of testing and calibration laboratories. Online [Accessed 28 November 2024] https://www.iso.org/standard/66912.html

[10] JCGM 100-3: 2008. Uncertainty of measurement, Part 3: Guide to the expression of uncertainty in measurement (GUM). Online [Accessed 28 November 2024] https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf

[11] EA-04/02 M: 2022. Evaluation of the Uncertainty of Measurement in Calibration. Online [Accessed 28 November 2024] https://www.enac.es/documents/7020/635abf3f-262a-4b3b-952f-10336cdfae9e

[12] Velychko O., Vendychanskyi R. 2022. Metrological traceability chains for high DC voltage and voltages ratio, Ukrainian Metrological Journal, 1: 57-61. doi: 10.24027/2306-7039.1.2022.258823

[13] Velychko O., Vendychanskyi R. 2022. Research of Long-Term Drift of the National High-Voltage DC Standard, 25th IMEKO TC4 International Symposium, Proceedings, September 12-14, Brescia, Italy, 102–106. doi: 10.21014/tc4-2022.19

[14] NIST/SEMATECH, 2012. e-Handbook of Statistical Methods. Online [Accessed 28 November 2024] https://www.itl.nist.gov/div898/handbook/

[15] J.-M. Pou and L. Leblond. 2019. Evaluate and quantify the drift of a measuring instrument, Proc. of 19th Intern. Congress of Metrology, 12004, p. 13. doi: https://doi.org/10.1051/metrology/201912004

[16] The BIPM key comparison database (KCDB). Online [Accessed 28 November 2024] http://kcdb.bipm.org.

[17] Kiselev V. *et al*. 2024. Supplementary comparisons of DC high voltage measuring reference instruments COOMET 449Ru-a08 (COOMET_EM-S7), Metrologia, 61(1A): 01002. doi: 10.1088/0026-1394/61/1A/01002.