Supplementary comparisons of national standards of ratio error and phase displacement of AC voltage of power frequency
COOMET 411/RU-a/07 (COOMET.EM-S6)

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Abstract – The supplementary comparisons of national standards of ratio error and phase displacement of AC voltage of power frequency have been performed among the following national metrological institutes (NMIs): VNIIMS, MIKES-TKK, SP, CMI, LCOE, BIM and SE “Ukrmetrteststandard”. Its description and measurement results are presented below.

Index Terms – Comparisons, standard uncertainty, measurement, ratio error, phase displacement, transfer standard, AC voltage.

I. INTRODUCTION

Comparisons were carried out in 2007 – 2011 under COOMET project 411/RU-a/07 (COOMET.EM-S6).

The Pilot laboratory of the comparisons was FGUP “VNIIMS”. The comparisons were performed with the FGUP “VNIIMS” transfer standard by each participating laboratory in turn using measuring equipment and voltage transformers for ratio error and phase displacement.

Because each laboratory made measurements at different voltages and ratios, the comparison results are treated as a sequence of bilateral comparisons with the pilot (VNIIMS).

II COMPARISON TRAVELLING STANDARD

Brief description of VNIIMS reference measurement system

The VNIIMS mobile reference system for transformer ratio K_U and phase displacement φ_U measurements is represented in Picture 1.

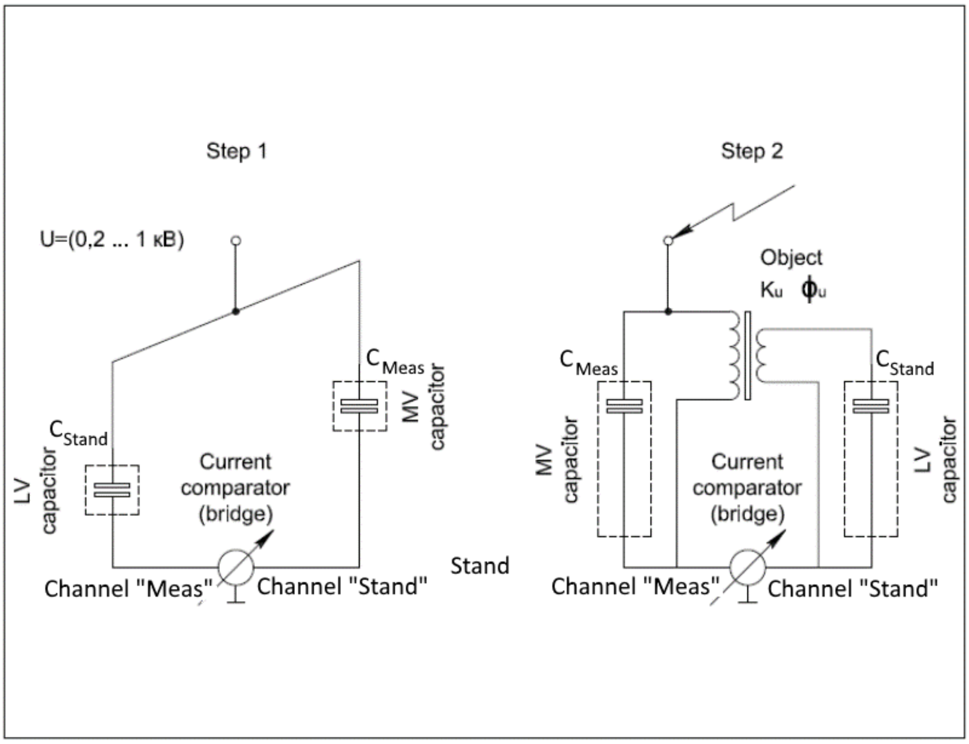
The reference system provides reproduction of values of K_U in the range from 0,1 to 2000 and φ_U in the range of 0 ... 0,1 rad of electric AC voltage of power frequency in the range of nominal values from 0.1 / √3 to 110 / √3 kV.

Picture 1 - VNIIMS reference measuring system (RMS)

The method of measurement of ratio error and phase displacement by means of the VNIIMS reference system is divided into three steps.

The first two steps are self-calibration of the reference standard. The third step is the measurement of the calibrated (investigated) transformer characteristics. If it is not necessary to check the product of the ratios of the reference capacitor to the measured capacitor and vice versa, then the second and third steps can be combined. The block diagram of self-calibration of the VNIIMS reference system and measurement of the characteristics of the voltage transformer is represented on Picture 2.

The ratio of currents and the ratio of phase displacements are set by reference low-voltage and high-voltage AC capacitors and compared by the reference high-voltage bridge (AC comparator) on the inputs: low-voltage (reference) and high-voltage (measured).



Picture 2 - Self-calibration of VNIIMS reference system and measurement of the characteristics of the voltage transformer

The VNIIMS reference system was self-calibrated before the measurements were made by each participant. The results of the self-calibration were stored in the reference comparator memory.

III. MEASURED VALUES

Two values were measured during comparisons: voltage ratio error - (ε) and phase displacement - (δ_U). Voltage error is defined as:

$$\varepsilon = \frac{U_2 \cdot K_U - U_1}{U_1} \cdot 10^6 , \qquad (1)$$

In this case, ratio error is derived from the values of the reference capacitors and the number of turns of the windings of the test object, and phase displacement is defined as the phase difference between the secondary U_2 and primary U_1 voltages of the current transformer.

IV. SCHEDULE OF THE COMPARISONS

Table 1 – Schedule of the comparisons

№	NMI		Country	Dates of measurements
pilot	VNIIMS	Russian research institute for metrological service (VNIIMS)	Russian Federation	2007 - 2010
1	MIKES-TKK	MIKES-TKK (including former Helsinki University of Technology - HUT)	Finland	from 18th to 26th of September 2007
2	SP	SP Technical Research Institute of Sweden	Sweden	from 15th to 21st of June 2008
3	CMI	Czech Metrology Institute (CMI)	Czech Republic	from 29th of June to 05th of July 2009
4	LCOE	Laboratorio Central Oficial de Electrotecnia (LCOE)	Spain	from the 05th to the 10th of October 2009
5	BIM	Bulgarian Institute of Metrology (BIM)	Bulgaria	from the 19th to the 23rd of April 2010; from the 01st to the 12th of November 2010
6	SE “Ukrmetrteststandard”	State enterprise “All-Ukrainian state research and production center for standardization, metrology, certification and consumers’ rights protection” (SE “Ukrmetrteststandard”)	Ukraine	August - October 2010

V. PARTICIPANT’S CAPABILITIES

For the comparisons, NMIs made available national standards with the following metrological characteristics:

VNIIMS used national standard with: rated value of primary voltage: U_1 = (1 – 100) kV; rated value of secondary voltage:
U_2 = (1 – 100) V; standard uncertainty of ratio error u (ε_{VNIIMS}) = 16 x 10^{-4};
standard uncertainty of phase displacement u (δ_{VNIIMS}) = 0,05'.

MIKES-TKK used national standard with: U_1 = (1 – 200) kV; U_2 = (1 – 200) V;
u ($\varepsilon_{MIKES-TKK}$) = 2 x 10^{-3};
u ($\delta_{MIKES-TKK}$) = [0,03 – 0,04]'.

SP used national standard with: U_1 = (1 – 100) kV; U_2 = (1 – 100) V;
u (ε_{SP}) = [16-22] x 10^{-4};
u (δ_{SP}) = [0,020-0,022]'.

CMI used national standard with: U_1 = (1 – 100) kV; U_2 = (1 – 250) V;
u (ε_{CMI}) = 18 x 10^{-4}; u (δ_{CMI}) = 0,055'.

LCOE used national standard with: U_1 = (1 – 100) kV; U_2 = (1 – 100) V;
u (ε_{LCOE}) = [3-5]×10^{-3}; u (δ_{LCOE}) = [0,10-0,30]'.

BIM used national standard with: U_1 = (1 –100) kV; U_2 = (1 - 100) V;
u (ε_{BIM}) = 5 x 10^{-3}; u (δ_{BIM}) = 0,2'.

SE "Ukrmetrteststandard" used national standard with: U_1 = (1 –330/3) kV;
U_2 = (100/3 – 150) V;
u ($\varepsilon_{\text{Ukrmetrteststandard}}$) = 2 x 10^{-3};
u ($\delta_{\text{Ukrmetrteststandard}}$) = 0,12'.

VI. PARTICIPANT'S REFERENCE EQUIPMENT

Voltage transformers of laboratories of participating NMIs stable in time with metrological characteristics presented below were used as objects of comparisons:

- MIKES-TKK: Haefely (VEOT) – rated primary voltage: $110/\sqrt{3}$ kV, rated secondary voltages: $110/\sqrt{3}$ V, $110/3$ V, $100/3$ V; rated values of transformation ratio: 1000, 1732, 1905; Strömberg (KRES 24 A2) - rated primary voltage: $20/\sqrt{3}$ kV, rated secondary voltages: $100/\sqrt{3}$ V, $100/3$ V; rated values of transformation ratio: 200, 346;

- SP: MWB NUZG 40 - rated primary voltage: 40 kV, 3 kV; rated secondary voltage: 100 V; rated values of transformation ratio: 400, 30; MWB NUEO 400 – rated primary voltages: $396/\sqrt{3}$ kV, $220/\sqrt{3}$ kV, $154/\sqrt{3}$ kV, $132/\sqrt{3}$ kV; rated secondary voltages: $110/\sqrt{3}$ V, $110/3$ V, $100/3$ V; rated values of transformation ratio: 3600, 2000, 1400, 1200;

– CMI: TETTEX 4820 - rated primary voltage: 22 kV; rated secondary voltages: 100 V, 110 V; rated value of transformation ratio: 220; TETTEX 4823 - rated primary voltages: 5 kV, 10 kV; rated secondary voltage: 100 V; rated values of transformation ratio: 50, 100; TETTEX 4825 - rated primary voltages: 50 kV, 100 kV, 200 kV; rated secondary voltage: 100 V; rated value of transformation ratio: 500;

– LCOE: TETTEX 4821 - rated primary voltages: 200-500 V; rated secondary voltage: 100 V; rated values of transformation ratio: 200/100, 500/100; TETTEX 4822 - rated primary voltages: 1000-2000 V; rated secondary voltage: 100 V; rated values of transformation ratio: 200/100, 500/100; TETTEX 4823 - rated primary voltages: 5000-10000 V; rated secondary voltage: 100 V; rated values of transformation ratio: 5000/100, 10000/100; TETTEX 2824 - rated primary voltages: 20000-50000 V; rated secondary voltage: 100 V; rated values of transformation ratio: 5000/100,10000/100; TETTEX 4829A - rated primary voltages: 3/5/6/10/15/20/25/30/35 kV; rated secondary voltages: 100 - 110 V; rated values of transformation ratio: 3 000 / 100– 5 000 / 100 – 6 000 / 100 – 10 000 / 100 – 15 000 / 100 – 20 000 / 100 – 25 000 / 100 – 30 000 / 100 – 35 000 / 100 - 3 000 / 110 – 5 000 / 110 – 6 000 / 110 – 10 000 / 110 – 15 000 / 110 – 20 000 / 110 – 25 000 / 110 – 30 000 / 110 – 35 000 / 110;

– BIM: TETTEX 4823 - rated primary voltages: 5 kV, 10 kV; rated secondary voltage: 100 V; rated values of transformation ratio: 50, 100; HK-II-40,5 - rated primary voltage: 35 kV; rated secondary voltage: 100 V; rated value of transformation ratio: 350;

– UKRMETRTESTSTANDARD: 4820spez - rated primary voltages: 110/√3 kV, 220/√3 kV, 330/√3 kV; rated secondary voltage: 100/√3 V; rated values of transformation ratio: 110000/√3:100/√3, 220000/√3:100/√3, 330000/√3:100/√3.

VII. METHODS AND MEASUREMENT PROCEDURE

Comparisons of the standard of the Russian Federation (VNIIMS) with the standards of Finland (MIKES-TKK) and Sweden (SP) use a capacitance bridge based method for determining the ratio error and phase displacement characteristics of the comparisons artefact. This method is based on the comparison of the currents that were connected both to the primary and to the secondary windings of the object under test (Figure 1), flowing through the reference capacitors.

The ratio error of the tested object is derived from the capacitance and windings ratios, and the phase displacement from the difference of phase displacements of the capacitors and the out of phase reading of the current comparator bridge.

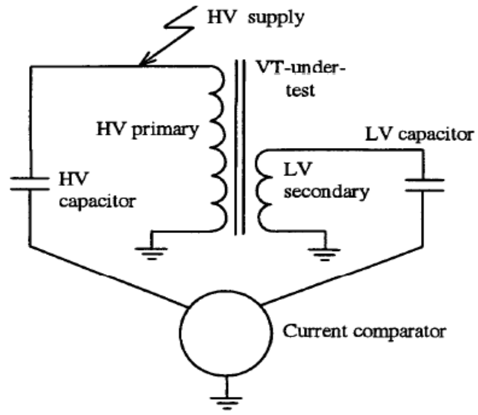


Figure 1

CMI used a capacitive and electronic divider as a standard and an automatic transformer set for error evaluation (Figure 2).

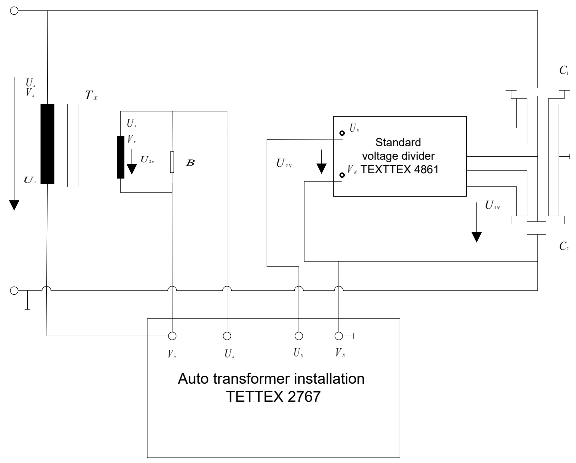


Figure 2

LCOE used the method based on a voltage transformer test system composed by a standard voltage transformer and a ratio comparator bridge with its own measuring software for determining the ratio error and phase displacement characteristics of the comparison artefact. The error finding of the test transformers happens by measuring of absolute quantity of transformer voltage. This principle makes the consideration of different secondary voltages by software possible.

BIM used the method based on a standard high voltage divider, capacitive divider with electronic device on output, then a differential test set and electronic voltage burden for determining the ratio error and phase displacement characteristics of the comparisons artefact.

UKRMETRTESTSTANDARD used the method of comparison with the standard voltage transformer using the current comparator bridge.

VIII. ANALYSIS OF COMPARISON DATA

The following ranges of rated voltage were used: 120, 100, 80, 60, 40 % of rated voltage value of the tested object. Measurements were made at the 50 Hz frequency.

For each combination of voltage steps the resulting comparison reference value (CRV) of the ratio error for each bilateral supplementary comparison is calculated as the weighted mean of results of measurements presented by the participant NMI and VNIIMS:

$$\varepsilon_r = \frac{\sum_{L=1}^{2} \varepsilon_L u^{-2}(\varepsilon_L)}{\sum_{L=1}^{2} u^{-2}(\varepsilon_L)} \quad (2)$$

with standard uncertainty:

$$u(\varepsilon_r) = \frac{1}{\sqrt{\sum_{l=1}^{2} u^{-2}(\varepsilon_L)}} \quad (3)$$

The difference in the participant's result to the CRV is given by:

$$\Delta(\varepsilon_L) = \varepsilon_L - \varepsilon_r$$

with uncertainty

$$u(\Delta\varepsilon_L) = \sqrt{u^2(\varepsilon_L) - u^2(\varepsilon_r)} \quad (4)$$

Similar formulae apply to the calculation of the phase error.

The credibility of the reference values and their uncertainties are characterized by the χ^2 test, given by the formulae (5) and (6). Values of this function are determined for the results of voltage ratio error χ_ε^2 and phase displacement χ_δ^2 measurement for each transformation ratio k_u at all operation voltages and burdens are determined by formulae:

$$\chi_\varepsilon^2 = \sum_{L=1}^{n} \frac{(\varepsilon_L - \varepsilon_r)^2}{u^2(\varepsilon_L)}, \quad (5)$$

$$\chi_\delta^2 = \sum_{L=1}^{n} \frac{(\delta_L - \delta_r)^2}{u^2(\delta_L)}, \quad (6)$$

where ε_r, δ_r - reference values of ratio error and phase displacement measurements;

ε_L, δ_L - are the results of voltage ratio error and phase displacement measurements for each NMI participating in the particular bilateral comparison (VNIIMS and one other participant);

$u(\varepsilon_L)$, $u(\delta_L)$ - combined standard uncertainties of voltage ratio error and phase displacement represented by each NMI participating in the particular bilateral comparison;

n – a number of NMIs participating in comparisons (equals 2 for bilateral comparisons).

IX. RESULTS OF COMPARISONS

Distribution function χ^2 is tabulated in Annex A. The received values χ^2_ε and χ^2_δ do not exceed the critical value $\chi^2_{0,95}(n-1)$ for the confidence level P = 0,95 and number of degrees of freedom (n-1, that is 1 for the bilateral comparisons), that is an objective evidence of uncertainties declared by NMI during the comparisons:

$$\chi^2_\varepsilon < \chi^2_{0,95}(n-1), \qquad (7)$$

$$\chi^2_\delta < \chi^2_{0,95}(n-1). \qquad (8)$$

$$\chi^2 < 3.841 \qquad (9)$$

Graphic results of comparisons for ratio error are demonstrated on examples below (Figures 3-8).

Standard uncertainties had been used in the calculation of equivalence graphs represented below.

More detailed presentation of results of comparisons of ratio error in the form of the Tables A.1.1 – A 1.6, including the results of measurements of all NMI participating the comparisons, may be found in Annex A.

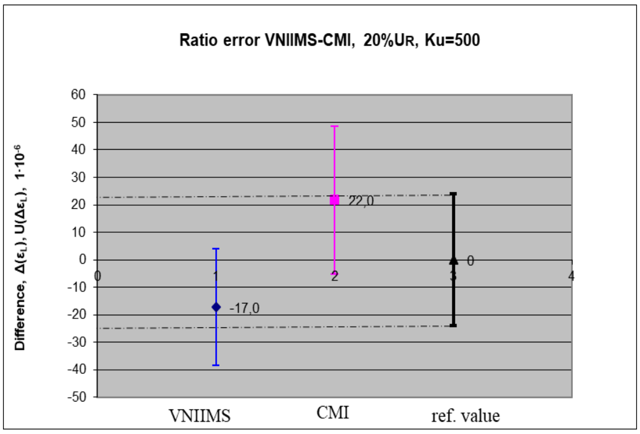


Figure. 3. Results of comparisons of ratio error between VNIIMS and CMI (results farthest located from the reference values)

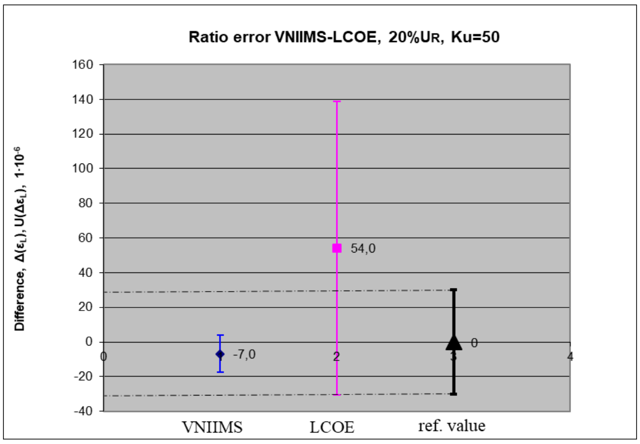


Figure. 4. Results of comparisons of ratio error between VNIIMS and LCOE (results farthest located from the reference values)

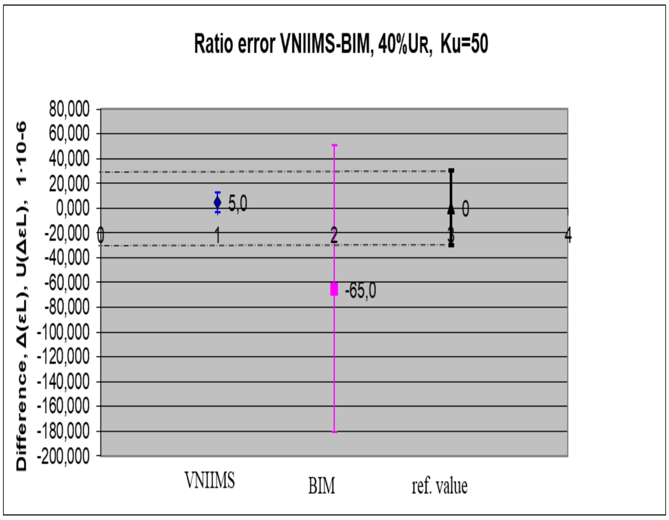


Figure. 5. Results of comparisons of ratio error between VNIIMS and BIM (results farthest located from the reference values)

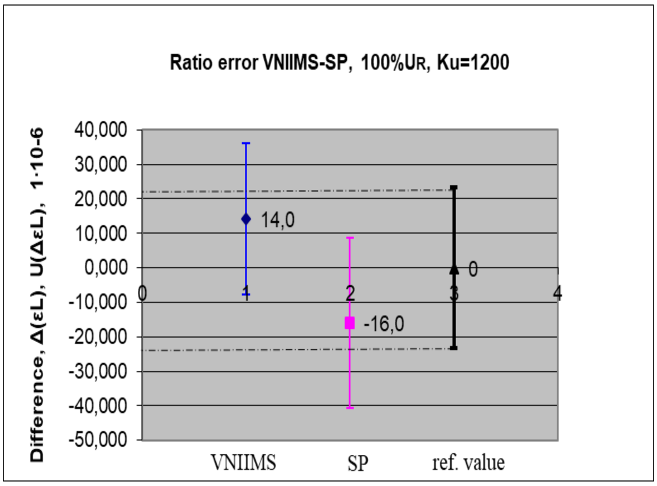


Figure. 6. Results of comparisons of ratio error between VNIIMS and SP (results farthest located from the reference values)

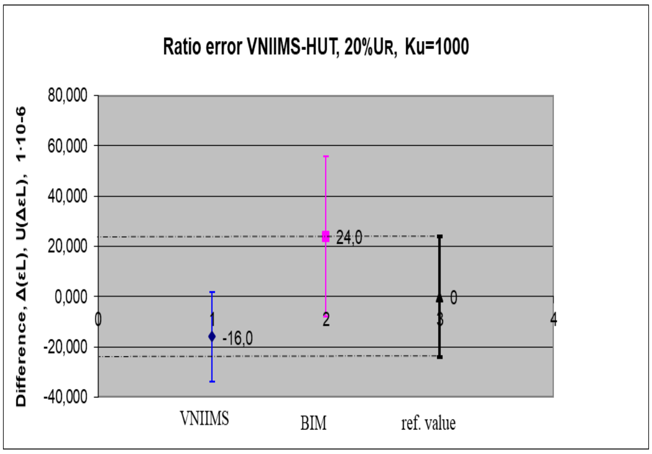


Figure. 7. Results of comparisons of ratio error between VNIIMS and HUT (results farthest located from the reference values)

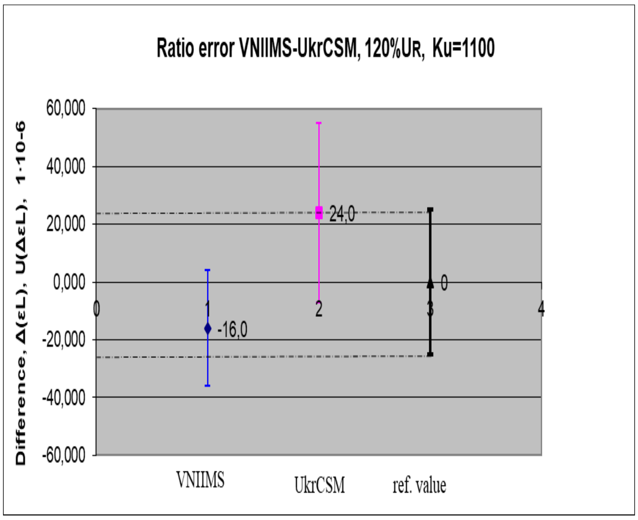


Figure. 8. Results of comparisons of ratio error between VNIIMS and UkrCSM (results farthest located from the reference values)

Graphic results of comparisons for phase displacement are demonstrated on examples below (Figures 9-14).

More detailed presentation of results of comparisons of phase displacement in the form of the Tables A 2.1 – A 2.6, including the results of measurements of all NMI participating the comparisons, may be found in Annex A.

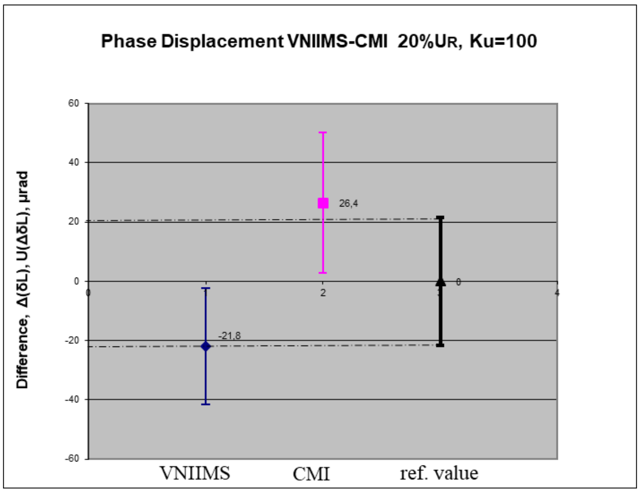


Figure. 9. Results of comparisons of phase displacement between VNIIMS and CMI (results farthest located from the reference values)

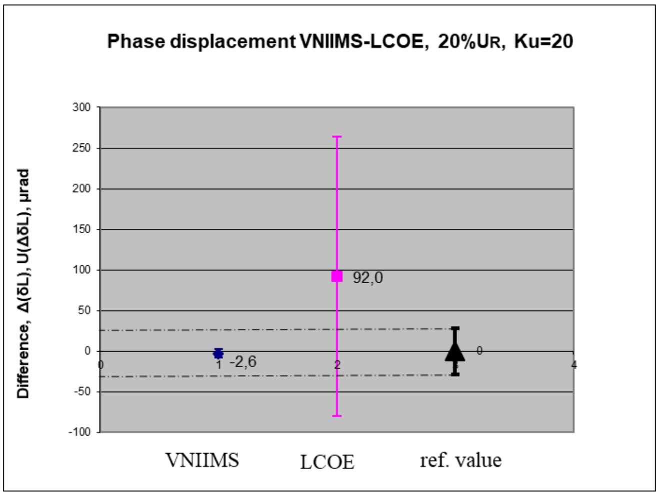


Figure. 10. Results of comparisons of phase displacement between VNIIMS and LCOE (results farthest located from the reference values)

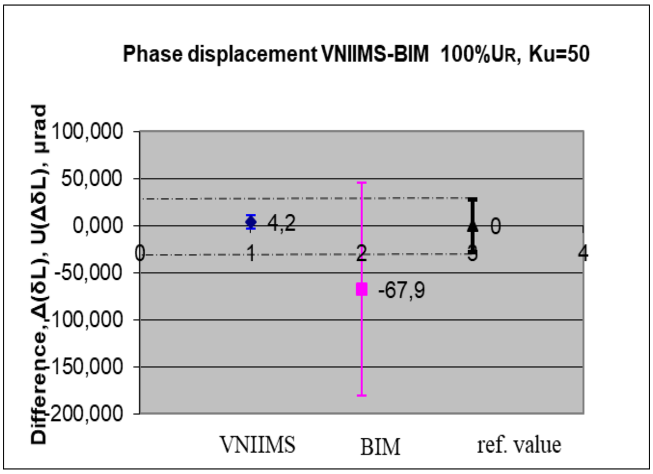


Figure. 11. Results of comparisons of phase displacement between VNIIMS and BIM (results farthest located from the reference values)

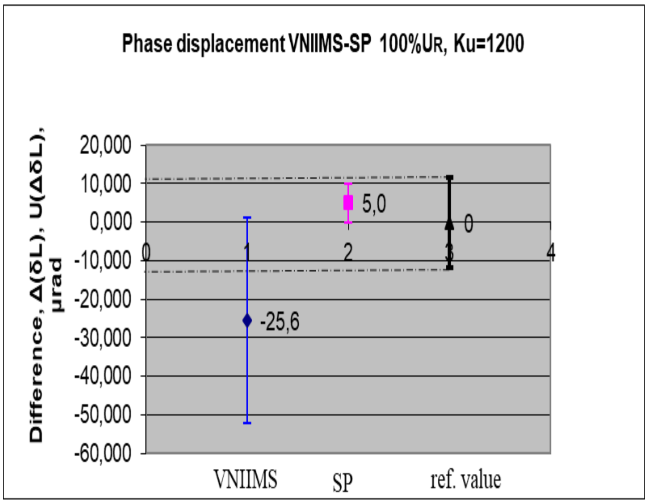


Figure. 12. Results of comparisons of phase displacement between VNIIMS and SP (results farthest located from the reference values)

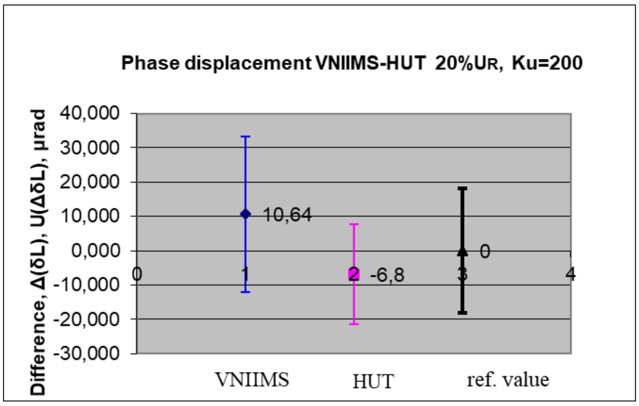


Figure. 13. Results of comparisons of phase displacement between VNIIMS and HUT (results farthest located from the reference values)

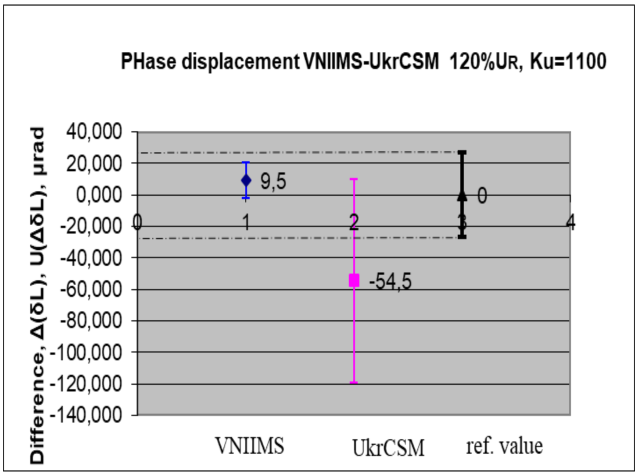


Figure. 14. Results of comparisons of phase displacement between VNIIMS and UkrCSM (results farthest located from the reference values)

X. CONCLUSION

All data presented by NMIs during the measurements, calculation and processing of the results of comparisons is recognized as consistent, being an objective evidence of uncertainties declared during the present comparisons under the COOMET project.

This is also the evidence of corresponding measurement and calibration capabilities for those values of voltage ratio error and phase displacement of AC high voltage of power frequency and may be approved and are the objective confirmation of the uncertainties, for the BIPM database.

Besides, for NMIs having a higher accuracy of measurements results may be accepted as the grounds for corresponding changes to the BIPM database based on the agreed protocols of comparisons with the improved uncertainties of the state standards.

Annex A

Table A.1.1 – Results of comparisons of ratio error VNIIMS – HUT

K_u	**Voltage range** $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{HUT}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{HUT}$, %	χ^2
1000	**120**	0,3108	0,0013	0,0025	-0,0008	0,0012	0,0016	0,002	0,6098
	100	0,3152	0,0013	0,0025	-0,0012	0,0018	0,0016	0,002	1,3720
	80	0,3178	0,0013	0,0025	-0,0008	0,0012	0,0016	0,002	0,6098
	60	0,3188	0,0013	0,0025	-0,0008	0,0012	0,0016	0,002	0,6098
	40	0,3169	0,0013	0,0025	-0,0004	0,0006	0,0016	0,002	0,1524
	20	0,3086	0,0013	0,0025	-0,0016	0,0024	0,0016	0,002	2,4390
200	**120**	0,4591	0,0013	0,0025	0,0001	-0,0001	0,0016	0,002	0,0061
	100	0,4751	0,0013	0,0025	0,0001	-0,0001	0,0016	0,002	0,0061
	80	0,4821	0,0013	0,0025	-0,0002	0,0002	0,0016	0,002	0,0244
	60	0,4851	0,0013	0,0025	0,0001	-0,0001	0,0016	0,002	0,0061
	40	0,4810	0,0013	0,0025	-0,0003	0,0001	0,0016	0,002	0,0377
	20	0,4671	0,0013	0,0025	0,0001	-0,0001	0,0016	0,002	0,0067
346	**120**	3,0112	0,00125	0,0025	0,0001	-0,0001	0,0016	0,002	0,0061
	100	3,0492	0,00125	0,0025	0,0001	-0,0002	0,0016	0,002	0,0137
	80	3,0651	0,00125	0,0025	0,0001	-0,0001	0,0016	0,002	0,0064
	60	3,0700	0,00125	0,0025	0	0	0,0016	0,002	0
	40	3,0637	0,00125	0,0025	-0,0007	0,0010	0,0016	0,002	0,4405
	20	3,0326	0,00125	0,0025	0,0002	-0,0004	0,0016	0,002	0,0549

Table A.1.2 – Results of comparisons of ratio error VNIIMS – SP

K_u	**Voltage range** $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{SP}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{SP}$, %	χ^2
1200	**120**	-0,0283	0,0013	0,0026	0,0003	-0,0007	0,0016	0,0022	0,1363
	100	-0,0324	0,0012	0,0023	0,0014	-0,0016	0,0016	0,0017	1,6514
	80	-0,0379	0,0012	0,0023	0,0009	-0,0011	0,0016	0,0017	0,7351
	60	-0,0459	0,0012	0,0023	0,0009	-0,0011	0,0016	0,0017	0,7351
	40	-0,0585	0,0012	0,0023	0,0005	-0,0005	0,0016	0,0017	0,1842
400	**100**	-0,0035	0,0011	0,0023	0,0005	-0,0005	0,0016	0,0016	0,1953
	80	-0,0030	0,0011	0,0023	0,0000	0,0000	0,0016	0,0016	0,0000
	60	-0,0020	0,0011	0,0023	0,0000	0,0000	0,0016	0,0016	0,0000
	40	0,0000	0,0011	0,0023	0,0000	0,0000	0,0016	0,0016	0,0000
	20	0,0045	0,0011	0,0023	-0,0005	0,0005	0,0016	0,0016	0,1953
200	**120**	-0,0040	0,0011	0,0023	0,0010	-0,0010	0,0016	0,0016	0,7813
	100	-0,0030	0,0011	0,0023	0,0010	-0,0010	0,0016	0,0016	0,7813
	80	-0,0030	0,0011	0,0023	0,0010	-0,0010	0,0016	0,0016	0,7813
	60	-0,0025	0,0011	0,0023	0,0005	-0,0005	0,0016	0,0016	0,1953
	40	-0,0010	0,0011	0,0023	0,0010	-0,0010	0,0016	0,0016	0,7813

Table A.1.3 – Results of comparisons of ratio error VNIIMS – CMI

K_u	**Voltage range** $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{CMI}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{CMI}$, %	χ^2
220	**120**	-0,0023	0,0012	0,0024	-0,0007	0,0008	0,0016	0,0018	0,3889
	100	-0,0017	0,0012	0,0024	-0,0003	0,0003	0,0016	0,0018	0,0630
	80	-0,0034	0,0012	0,0024	-0,0006	0,0008	0,0016	0,0018	0,3382
	60	-0,0057	0,0012	0,0024	-0,0003	0,0003	0,0016	0,0018	0,0623
	40	-0,0100	0,0012	0,0024	0,0000	0,0000	0,0016	0,0018	0,0000
100	**100**	-0,0035	0,0012	0,0024	-0,0009	0,0011	0,0016	0,0018	0,6899
	80	-0,0105	0,0012	0,0024	-0,0008	0,0009	0,0016	0,0018	0,4983
	60	-0,0239	0,0012	0,0024	-0,0008	0,0009	0,0016	0,0018	0,4983
	40	-0,0466	0,0012	0,0024	-0,0001	0,0001	0,0016	0,0018	0,0070
	20	-0,0945	0,0012	0,0024	-0,0002	0,0003	0,0016	0,0018	0,0434
50	**120**	0,0320	0,0012	0,0024	-0,0013	0,0017	0,0016	0,0018	1,5521
	100	0,0229	0,0012	0,0024	-0,0009	0,0011	0,0016	0,0018	0,6899
	80	-0,0097	0,0012	0,0024	0,0010	-0,0013	0,0016	0,0018	0,9122
	60	-0,0083	0,0012	0,0024	-0,0004	0,0006	0,0016	0,0018	0,1736
	40	-0,0381	0,0012	0,0024	-0,0007	0,0008	0,0016	0,0018	0,3889
	20	-0,0980	0,0012	0,0024	-0,0011	0,0013	0,0016	0,0018	0,9943
500	**120**	-0,0260	0,0012	0,0024	-0,0008	0,0011	0,0016	0,0018	0,6235
	100	-0,0267	0,0012	0,0024	-0,0010	0,0012	0,0016	0,0018	0,8351
	80	-0,0277	0,0012	0,0024	-0,0010	0,0012	0,0016	0,0018	0,8351
	60	-0,0294	0,0012	0,0024	-0,0012	0,0016	0,0016	0,0018	1,3526
	40	-0,0317	0,0012	0,0024	-0,0012	0,0016	0,0016	0,0018	1,3526
	20	-0,0362	0,0012	0,0024	-0,0017	0,0022	0,0016	0,0018	2,6227

Table A.1.4 – Results of comparisons of ratio error VNIIMS – LCOE

K_u	**Voltage range** $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{LCOE}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{LCOE}$, %	χ^2
20	**120**	0,0559	0,0014	0,0028	0,0001	-0,0002	0,0016	0,003	0,0084
	100	0,0668	0,0014	0,0028	0,0002	-0,0007	0,0016	0,003	0,0701
	80	0,0698	0,0014	0,0028	0,0002	-0,0007	0,0016	0,003	0,0701
	60	0,0690	0,0015	0,0030	0,0000	0,0002	0,0016	0,0045	0,0019
	40	0,0649	0,0015	0,0030	0,0001	-0,0009	0,0016	0,0045	0,0439
	20	0,0516	0,0018	0,0037	0,0004	-0,0020	0,0020	0,0045	0,2375
50	**120**	0,0130	0,0014	0,0028	0,0000	0,0002	0,0016	0,003	0,0044
	100	0,0112	0,0014	0,0028	-0,0002	0,0007	0,0016	0,003	0,0701
	80	0,0082	0,0014	0,0028	-0,0002	0,0005	0,0016	0,003	0,0434
	60	0,0041	0,0014	0,0028	-0,0001	0,0003	0,0016	0,003	0,0139
	40	-0,0049	0,0015	0,0030	-0,0001	0,0004	0,0016	0,0045	0,0118
	20	-0,0273	0,0015	0,0030	-0,0007	0,0054	0,0016	0,0045	1,6314
100	**120**	-0,0101	0,0014	0,0028	0,0001	-0,0005	0,0016	0,003	0,0317
	100	0,0023	0,0014	0,0028	-0,0003	0,0009	0,0016	0,003	0,1252
	80	0,0070	0,0014	0,0028	0,0000	0,0000	0,0016	0,003	0,0000
	60	0,0071	0,0014	0,0028	-0,0001	0,0005	0,0016	0,003	0,0317
	40	0,0035	0,0014	0,0028	0,0005	-0,0016	0,0016	0,003	0,3821
	20	-0,0090	0,0015	0,0030	0,0000	-0,0003	0,0016	0,0045	0,0044
200	**120**	0,0045	0,0014	0,0028	-0,0005	0,0019	0,0016	0,003	0,4988
	100	0,0045	0,0014	0,0028	-0,0005	0,0017	0,0016	0,003	0,4188
	80	0,0034	0,0014	0,0028	-0,0004	0,0015	0,0016	0,003	0,3125
	60	0,0012	0,0014	0,0028	-0,0002	0,0008	0,0016	0,003	0,0867
	40	-0,0018	0,0014	0,0028	-0,0002	0,0009	0,0016	0,003	0,1056
	20	-0,0067	0,0015	0,0030	-0,0003	0,0026	0,0016	0,0045	0,3689

End of Table A.1.4

K_u	Voltage range $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{LCOE}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{LCOE}$, %	χ^2
250	**120**	-0,0042	0,0014	0,0028	0,0002	-0,0008	0,0016	0,003	0,0867
	100	-0,0043	0,0014	0,0028	0,0003	-0,0009	0,0016	0,003	0,1252
	80	-0,0041	0,0014	0,0028	0,0001	-0,0005	0,0016	0,003	0,0318
	60	-0,0042	0,0014	0,0028	0,0002	-0,0005	0,0016	0,003	0,0434
	40	-0,0032	0,0014	0,0028	0,0002	-0,0005	0,0016	0,003	0,0434
	20	-0,0020	0,0015	0,0030	0,0000	0,0005	0,0016	0,005	0,0091
350	**120**	-0,0068	0,0014	0,0028	-0,0002	0,0009	0,0016	0,003	0,1056
	100	-0,0068	0,0014	0,0028	-0,0002	0,0005	0,0016	0,003	0,0434
	80	-0,0068	0,0014	0,0028	-0,0002	0,0005	0,0016	0,003	0,0434
	60	-0,0067	0,0014	0,0028	-0,0003	0,0012	0,0016	0,003	0,1952
	40	-0,0049	0,0014	0,0028	-0,0001	0,0005	0,0016	0,003	0,0317
	20	-0,0020	0,0015	0,0030	0,0000	0,0005	0,0016	0,005	0,0091
500	**120**	-	-	-	-	-	-	-	-
	100	-	-	-	-	-	-	-	-
	80	0,0016	0,0014	0,0028	0,0004	-0,0012	0,0016	0,003	0,2225
	60	0,0001	0,0014	0,0028	0,0002	-0,0007	0,0016	0,003	0,0701
	40	-0,0034	0,0014	0,0028	0,0004	-0,0012	0,0016	0,003	0,2225
	20	-0,0081	0,0015	0,0030	0,0001	-0,0004	0,0016	0,0045	0,0118

Table A.1.5 – Results of comparisons of ratio error VNIIMS – BIM

K_u	**Voltage range** $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{BIM}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{BIM}$, %	χ^2
50	**120**	0,0297	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	100	0,0267	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	80	0,0247	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	60	0,0216	0,0015	0,0031	0,0004	-0,0056	0,0016	0,006	0,9336
	40	0,0185	0,0015	0,0031	0,0005	-0,0065	0,0016	0,006	1,2712
100	**120**	0,0266	0,0015	0,0031	0,0004	-0,0056	0,0016	0,006	0,9336
	100	0,0317	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	80	0,0337	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	60	0,0337	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	40	0,0305	0,0015	0,0031	0,0005	-0,0065	0,0016	0,006	1,2712
350	**120**	0,0717	0,0015	0,0031	0,0003	-0,0047	0,0016	0,006	0,6487
	100	0,0748	0,0015	0,0031	0,0002	-0,0028	0,0016	0,006	0,2334
	80	0,0749	0,0015	0,0031	0,0001	-0,0019	0,0016	0,006	0,1042
	60	0,0739	0,0015	0,0031	0,0001	-0,0019	0,0016	0,006	0,1042
	40	0,0719	0,0015	0,0031	0,0001	-0,0019	0,0016	0,006	0,1042
	20	0,0669	0,0015	0,0031	0,0001	-0,0019	0,0016	0,006	0,1042

Table A.1.6 – Results of comparisons of ratio error VNIIMS – Ukrmetrteststandard

K_u	**Voltage range** $U_{ном}[\%]$	$\varepsilon_r(\%)$	$u(\varepsilon_r)$, %	$U(\varepsilon_r)$, %	$\Delta(\varepsilon_L)_{VNIIMS}$, %	$\Delta(\varepsilon_L)_{Ukr}$, %	$u(\varepsilon_L)_{VNIIMS}$, %	$u(\varepsilon_L)_{Ukr}$, %	χ^2
1100 (S=0 VA)	**120**	-0,0100	0,0012	0,0025	0,0000	0,0000	0,0016	0,002	0,0000
	100	-0,0056	0,0012	0,0025	-0,0004	0,0006	0,0016	0,002	0,1525
	80	-0,0046	0,0012	0,0025	-0,0004	0,0006	0,0016	0,002	0,1525
	60	-0,0056	0,0012	0,0025	-0,0004	0,0006	0,0016	0,002	0,1525
	40	-0,0082	0,0012	0,0025	-0,0008	0,0012	0,0016	0,002	0,6100
1100 (S=1,25 VA)	**120**	-0,0144	0,0012	0,0025	-0,0016	0,0024	0,0016	0,002	2,4400
	100	-0,0088	0,0012	0,0025	-0,0012	0,0018	0,0016	0,002	1,3720
	80	-0,0078	0,0012	0,0025	-0,0012	0,0018	0,0016	0,002	1,3720
	60	-0,0088	0,0012	0,0025	-0,0012	0,0018	0,0016	0,002	1,3720
	40	-0,0108	0,0012	0,0025	-0,0012	0,0018	0,0016	0,002	1,3720

Table A.2.1 – Results of comparisons of phase displacement VNIIMS – HUT

K_u	**Voltage range** $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{HUT}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{HUT}$	χ^2
1000	**120**	257,37599	7,48303	14,96606	0,64166	-0,23100	14,54440	8,72664	0,00265
	100	211,67235	7,48303	14,96606	-1,06944	0,38500	14,54440	8,72664	0,00735
	80	179,12712	7,48303	14,96606	0,64166	-0,23100	14,54440	8,72664	0,00265
	60	153,39209	7,48303	14,96606	1,06944	-0,38500	14,54440	8,72664	0,00735
	40	133,01282	7,48303	14,96606	0,21389	-0,07700	14,54440	8,72664	0,00029
	20	141,28643	9,08581	18,17163	5,32112	-3,40552	14,54440	11,63552	0,21951
200	**120**	320,79813	7,48303	14,96606	4,70554	-1,69399	14,54440	8,72664	0,14235
	100	212,09157	7,48303	14,96606	8,98331	-3,23399	14,54440	8,72664	0,51882
	80	142,43245	7,48303	14,96606	9,41108	-3,38799	14,54440	8,72664	0,56941
	60	96,42082	7,48303	14,96606	6,84442	-2,46399	14,54440	8,72664	0,30118
	40	66,58769	7,48303	14,96606	9,62497	-3,46499	14,54440	8,72664	0,59559
	20	64,69775	9,08581	18,17163	10,64224	-6,81104	14,54440	11,63552	0,87805
346	**120**	-99,40670	7,48303	14,96606	7,48609	-2,69499	14,54440	8,72664	0,36029
	100	-198,33428	7,48303	14,96606	9,83886	-3,54199	14,54440	8,72664	0,62235
	80	-266,17108	7,48303	14,96606	10,48052	-3,77299	14,54440	8,72664	0,70618
	60	-330,67977	7,48303	14,96606	6,63054	-2,38699	14,54440	8,72664	0,28265
	40	-401,11744	7,48303	14,96606	8,12775	-2,92599	14,54440	8,72664	0,42471
	20	-467,57053	9,08581	18,17163	7,09483	-4,54069	14,54440	11,63552	0,39024

Table A.2.2 – Results of comparisons of phase displacement VNIIMS – SP

K_u	**Voltage range** $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{SP}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{SP}$	χ^2
1200	**120**	63,03535	5,85759	11,71518	-19,98393	3,86889	14,54440	6,39954	2,25335
	100	67,76794	5,85759	11,71518	-25,58918	4,95406	14,54440	6,39954	3,69471
	80	68,92720	5,63206	11,26413	-21,51246	3,79480	14,54440	6,10865	2,57361
	60	77,65384	5,63206	11,26413	-21,51246	3,79480	14,54440	6,10865	2,57361
	40	89,15851	5,63206	11,26413	-22,25427	3,92565	14,54440	6,10865	2,75416
400	**100**	-16,77120	5,40165	10,80331	4,26301	-0,68208	14,54440	6,10865	0,09838
	80	-11,11393	5,40165	10,80331	3,25995	-0,52159	14,54440	5,81776	0,05828
	60	0,28086	5,40165	10,80331	1,75536	-0,28086	14,54440	5,81776	0,01690
	40	20,72326	5,40165	10,80331	2,25689	-0,36110	14,54440	5,81776	0,02793
	20	56,41221	5,40165	10,80331	-11,03368	1,76539	14,54440	5,81776	0,66759
200	**120**	-1,02312	5,40165	10,80331	11,78598	-1,88576	14,54440	5,81776	0,76172
	100	-16,04899	5,40165	10,80331	8,77679	-1,40429	14,54440	5,81776	0,42241
	80	-10,47197	5,40165	10,80331	7,27220	-1,16355	14,54440	5,81776	0,29000
	60	0,76233	5,40165	10,80331	4,76454	-0,76233	14,54440	5,81776	0,12448
	40	21,04424	5,40165	10,80331	4,26301	-0,68208	14,54440	5,81776	0,09965

Table A.2.3 – Results of comparisons of phase displacement VNIIMS – CMI

K_u	**Voltage range** $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{CMI}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{CMI}$	χ^2
220	**120**	-94,22402	10,76198	21,52397	-12,24099	14,81160	14,54440	15,99884	1,56543
	100	-79,01229	10,76198	21,52397	6,58118	-7,96322	14,54440	15,99884	0,45249
	80	-84,45361	10,76198	21,52397	-3,68546	4,45941	14,54440	15,99884	0,14190
	60	-64,68770	10,76198	21,52397	-1,05299	1,27412	14,54440	15,99884	0,01158
	40	-31,23558	10,76198	21,52397	-1,05299	1,27412	14,54440	15,99884	0,01158
100	**100**	235,73116	10,76198	21,52397	-4,47520	5,41499	14,54440	15,99884	0,20923
	80	243,01784	10,76198	21,52397	-7,10767	8,60028	14,54440	15,99884	0,52778
	60	269,10825	10,76198	21,52397	-9,34527	11,30778	14,54440	15,99884	0,91240
	40	317,54176	10,76198	21,52397	-12,10936	14,65233	14,54440	15,99884	1,53195
	20	458,18151	10,76198	21,52397	-21,84951	26,43790	14,54440	15,99884	4,98751
50	**120**	-29,48104	10,76198	21,52397	-10,66151	12,90042	14,54440	15,99884	1,18751
	100	-9,73909	10,76198	21,52397	-12,13569	14,68418	14,54440	15,99884	1,53861
	80	19,65324	10,76198	21,52397	-12,84646	15,54421	14,54440	15,99884	1,72412
	60	64,24808	10,76198	21,52397	-14,21534	17,20056	14,54440	15,99884	2,11113
	40	145,38609	10,76198	21,52397	-18,55892	22,45629	14,54440	15,99884	3,59837
	20	393,43589	10,76198	21,52397	-12,37261	14,97086	14,54440	15,99884	1,59928
500	**120**	-30,20365	10,76198	21,52397	-0,92136	1,11485	14,54440	15,99884	0,00887
	100	-26,36551	10,76198	21,52397	-5,92306	7,16690	14,54440	15,99884	0,36652
	80	-10,39431	10,76198	21,52397	-6,18631	7,48543	14,54440	15,99884	0,39982
	60	12,23967	10,76198	21,52397	-6,71280	8,12249	14,54440	15,99884	0,47077
	40	55,44378	10,76198	21,52397	-8,02904	9,71513	14,54440	15,99884	0,67348
	20	143,53414	10,76198	21,52397	-7,10767	8,60028	14,54440	15,99884	0,52778

Table A.2.4 – Results of comparisons of phase displacement VNIIMS – LCOE

K_u	Voltage range $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{LCOE}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{LCOE}$	χ^2
20	**120**	430,63060	13,00891	26,01781	1,91986	-7,67944	14,54440	29,08880	0,08712
	100	262,90457	13,00891	26,01781	2,38528	-9,54113	14,54440	29,08880	0,13448
	80	181,33958	13,00891	26,01781	1,91986	-7,67944	14,54440	29,08880	0,08712
	60	148,40005	14,34651	28,69302	0,24372	-8,77381	14,54440	87,26640	0,01039
	40	153,41590	14,34651	28,69302	0,46385	-16,69854	14,54440	87,26640	0,03763
	20	248,64635	14,34651	28,69302	-2,55510	91,98350	14,54440	87,26640	1,14189
50	**120**	-11,51916	13,00891	26,01781	-4,47968	17,91870	14,54440	29,08880	0,47432
	100	-17,10421	13,00891	26,01781	-0,93084	3,72337	14,54440	29,08880	0,02048
	80	-5,06145	13,00891	26,01781	0,40724	-1,62897	14,54440	29,08880	0,00392
	60	29,67058	13,00891	26,01781	-4,94510	19,78038	14,54440	29,08880	0,57800
	40	90,18314	14,34651	28,69302	-0,88053	31,69893	14,54440	87,26640	0,13561
	20	281,40662	14,34651	28,69302	0,17296	-6,22658	14,54440	87,26640	0,00523
100	**120**	349,88009	13,00891	26,01781	-6,63225	26,52899	14,54440	29,08880	1,03968
	100	168,54051	13,00891	26,01781	-2,44346	9,77384	14,54440	29,08880	0,14112
	80	88,02271	13,00891	26,01781	-1,62897	6,51589	14,54440	29,08880	0,06272
	60	60,44653	13,00891	26,01781	-6,63225	26,52899	14,54440	29,08880	1,03968
	40	79,06336	13,00891	26,01781	-9,83201	39,32806	14,54440	29,08880	2,28488
	20	168,52636	14,34651	28,69302	-2,13842	76,98312	14,54440	87,26640	0,79983

End of Table A.2.4

K_u	**Voltage range** $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{LCOE}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{LCOE}$	χ^2
200	**120**	-72,89653	13,00891	26,01781	-3,60701	14,42804	14,54440	29,08880	0,30752
	100	-82,14677	13,00891	26,01781	-1,62897	6,51589	14,54440	29,08880	0,06272
	80	-83,60121	13,00891	26,01781	-0,75631	3,02524	14,54440	29,08880	0,01352
	60	-73,24560	13,00891	26,01781	-4,71239	18,84954	14,54440	29,08880	0,52488
	40	-54,97783	13,00891	26,01781	-8,43575	33,74301	14,54440	29,08880	1,68200
	20	-32,46939	14,34651	28,69302	-1,85539	66,79417	14,54440	87,26640	0,60212
250	**120**	-36,88460	13,00891	26,01781	-1,51262	6,05047	14,54440	29,08880	0,05408
	100	-31,88132	13,00891	26,01781	-0,98902	3,95608	14,54440	29,08880	0,02312
	80	-21,99113	13,00891	26,01781	-1,57080	6,28318	14,54440	29,08880	0,05832
	60	-5,00327	13,00891	26,01781	-2,26893	9,07571	14,54440	29,08880	0,12168
	40	24,08553	13,00891	26,01781	-7,21402	28,85609	14,54440	29,08880	1,23008
	20	54,96997	14,34651	28,69302	-1,44658	52,07681	14,54440	87,26640	0,36601
350	**120**	-28,39067	13,00891	26,01781	-2,73435	10,93739	14,54440	29,08880	0,17672
	100	-28,68156	13,00891	26,01781	-3,31612	13,26449	14,54440	29,08880	0,25992
	80	-22,10749	13,00891	26,01781	-3,19977	12,79907	14,54440	29,08880	0,24200
	60	-8,08669	13,00891	26,01781	-3,83972	15,35889	14,54440	29,08880	0,34848
	40	14,95164	13,00891	26,01781	-5,64323	22,57291	14,54440	29,08880	0,75272
	20	47,34399	14,34651	28,69302	-2,25635	81,22851	14,54440	87,26640	0,89048
500	**120**								
	100								
	80	-44,27315	13,00891	26,01781	-4,88692	19,54767	14,54440	29,08880	0,56448
	60	-44,04044	13,00891	26,01781	-5,99229	23,96917	14,54440	29,08880	0,84872
	40	-33,16123	13,00891	26,01781	-9,01753	36,07011	14,54440	29,08880	1,92200
	20	-13,13713	14,34651	28,69302	-1,69816	61,13365	14,54440	87,26640	0,50439

Table A.2.5 – Results of comparisons of phase displacement VNIIMS – BIM

K_u	**Voltage range** $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{BIM}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{BIM}$	χ^2
50	**120**	39,21855	14,11014	28,22028	3,83288	-61,32603	14,54440	58,17764	1,18061
	100	62,07892	14,11014	28,22028	4,24354	-67,89668	14,54440	58,17764	1,44715
	80	77,03399	14,11014	28,22028	3,83288	-61,32603	14,54440	58,17764	1,18061
	60	111,73521	14,11014	28,22028	3,74732	-59,95715	14,54440	58,17764	1,12849
	40	149,34532	14,11014	28,22028	2,49821	-39,97143	14,54440	58,17764	0,50155
100	**120**	167,08949	14,11014	28,22028	-1,57422	25,18748	14,54440	58,17764	0,19915
	100	88,70373	14,11014	28,22028	-0,56466	9,03464	14,54440	58,17764	0,02562
	80	64,59425	14,11014	28,22028	-0,01711	0,27378	14,54440	58,17764	0,00002
	60	63,41358	14,11014	28,22028	0,00000	0,00000	14,54440	58,17764	0,00000
	40	100,42480	14,11014	28,22028	-0,35933	5,74932	14,54440	58,17764	0,01038
350	**120**	-149,87576	14,11014	28,22028	1,23200	-19,71194	14,54440	58,17764	0,12198
	100	-190,71986	14,11014	28,22028	0,77000	-12,31996	14,54440	58,17764	0,04765
	80	-197,78673	14,11014	28,22028	0,56466	-9,03464	14,54440	58,17764	0,02562
	60	-194,50141	14,11014	28,22028	0,77000	-12,31996	14,54440	58,17764	0,04765
	40	-184,59410	14,11014	28,22028	1,04377	-16,70039	14,54440	58,17764	0,08755
	20	-166,71305	14,11014	28,22028	0,90689	-14,51018	14,54440	58,17764	0,06609

Table A.2.6 – Results of comparisons of phase displacement VNIIMS – Ukrmetrteststandard

K_u	**Voltage range** $U_{ном}[\%]$	$\delta_r(\mu rad)$	$u(\delta_r)$	$U(\delta_r)$	$\Delta(\delta_L)_{VNIIMS}$	$\Delta(\delta_L)_{Ukr}$	$u(\delta_L)_{VNIIMS}$	$u(\delta_L)_{Ukr}$	χ^2
1100 (S=0 VA)	**120**	62,06758	13,42560	26,85120	7,74554	-44,61430	14,54440	34,90658	1,91716
	100	61,20697	13,42560	26,85120	8,60615	-49,57145	14,54440	34,90658	2,36686
	80	58,29809	13,42560	26,85120	8,60615	-49,57145	14,54440	34,90658	2,36686
	60	55,38921	13,42560	26,85120	8,60615	-49,57145	14,54440	34,90658	2,36686
	40	50,00175	13,42560	26,85120	8,17585	-47,09287	14,54440	34,90658	2,13609
1100 (S=1,25 VA)	**120**	45,80195	13,42560	26,85120	9,46677	-54,52859	14,54440	34,90658	2,86391
	100	39,98419	13,42560	26,85120	9,46677	-54,52859	14,54440	34,90658	2,86391
	80	35,02705	13,42560	26,85120	8,60615	-49,57145	14,54440	34,90658	2,36686
	60	42,23900	13,42560	26,85120	4,30308	-24,78572	14,54440	34,90658	0,59172
	40	35,66390	13,42560	26,85120	2,15154	-12,39286	14,54440	34,90658	0,14793