Bilateral Comparison of Voltage Transformer Measuring Systems of NCHVM and PTB

Xue Wang[1], Enrico Mohns[2], Chun Yang Jang[1], Peter Raether[2], Hong Yang[1]

[1] National Center For High Voltage Measurement , Wuhan, China, wangxue@epri.sgcc.com.cn
[2] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, enrico.mohns@ptb.de

Abstract −**An intercomparison of voltage transformer calibration systems was performed between National Center For High Voltage Measurement (NCHVM) and Physikalisch-Technische Bundesanstalt (PTB) in order to confirm their measurement capabilities. Two voltage transformers were used as travelling standards with transformer ratios of 10 kV / 100V and (110kV / √3) / 100V at a frequency of 50 Hz and at ambient temperatures of 23 °C ± 3 °C. The measurements has been performed at test points varying from 20% to 120% of the rated voltage. For the ratio of 10kV / 100V the test results differ by no more than 4 parts in 10^6 for the voltage ratio and 4 µrad for the phase displacement. For the ratio of (110kV / √ 3) / 100V the results agree within 2 parts in 10^6 for the voltage ratio and 9 µrad for the phase displacement.**

Keywords − voltage transformers, travelling standard, Bilateral comparison, uncertainty.

I. INTRODUCTION

In the comparison of the measurement of voltage transformers between the Institute for National Center For High Voltage Measurement (NCHVM) and the Physikalisch-Technische Bundesanstalt (PTB), two voltage transformers VT#1 and VT#2 were used as the travelling standards with voltage ratios of 10kV / 100V for VT#1 and (110 kV / √3) / 100V for VT#2. These travelling standards were calibrated in July 2018 using NCHVMs measurement system, and in October 2018 at PTBs instrument transformer laboratory. Interestingly, the traceability method for the voltage transformer standards are different. NCHVM makes use of an inductive summation method, while PTB makes use of a step-up method based on active capacitive dividers.

The calibration was performed at a frequency of 50 Hz, with a resistive burden of 40 kΩ for VT#1 and > 3 MΩ for VT#2. The test points vary from 20%, 50%, 80%, 100% and 120% of the rated voltage. The test results of the measured voltage ratio errors and phase displacements of PTB and NCHVM，the uncertainty calculation and the EN factor which indicate the equivalence degree of the

voltage transformer measurement systems, are described.

II. TRANSFER STANDARD

The travelling standard for the comparison were two voltage transformers VT#1 and VT#2, shown in Fig. 1 and Fig. 2, were manufactured by NCHVM with rated voltage ratios of 10kV / 100V and (110 kV / √3) / 100V and a rated frequency of 50 Hz.

Fig 1 Photograph of the VT#1 voltage travelling transformer(10kV)

Fig 2 Photograph of the VT#2 voltage travelling transformer(110kV)

The 10kV transformer is specified for error limits of 0.01 % (or crad) for the voltage error and the phase displacement at operating voltages of 20% up to 120% of

the rated voltage. The 110kV travelling standard is specified for error limits of 0.005 % (or crad) for the voltage error and phase displacement.

III. CALIBRATION SYSTEMS

A. NCHVM Calibration System

The traceability method of NCHVMs calibration system is based on the "Half-Symmetry Summation" (HSS) and is shown in Fig 3. The method is applied which in principle consists of three steps.
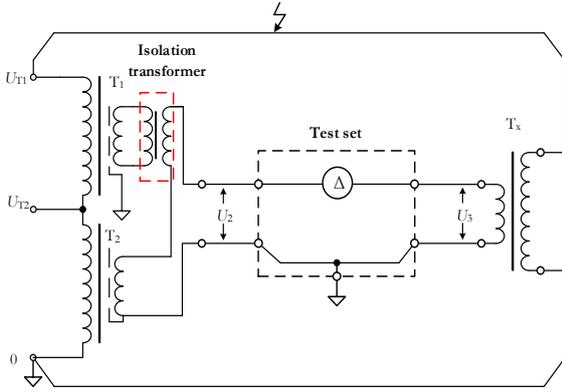

Fig. 3   HSS method measurement circuit.

Step 1) $U_{T2}=U$, $U_{T1}=U$ (the primary winding of T_1 is shorted), the error measured be the test set is denoted as $\dot{\varepsilon}_1$. here $\dot{\delta}$ is calculated as the added error of T_2. According to the error definition of voltage transformer:

$$\dot{\varepsilon}_1 = \frac{\dot{U}_{2TX} - \dot{U}_{2T2}}{\dot{U}_{2TX}} = 1 - \frac{1 + \dot{\beta}_U + \delta}{1 + \dot{\gamma}_U}$$
$$\approx \dot{\gamma}_U - (\dot{\beta}_U + \dot{\delta}) \qquad (1)$$

where, $\dot{U}_{2T2}$ and $\dot{U}_{2TX}$ are the secondary voltages of T_2 and T_X respectively, $\dot{\beta}_U$ and $\dot{\gamma}_U$ are the errors of T_2 and T_X under voltages of U respectively.

Step 2) $U_{T2}=0$, $U_{T1}=U$ (the primary winding of T_2 is shorted), the error measured be the test set is denoted as , similarly calculation process as above:

$$\dot{\varepsilon}_2 \approx \dot{\gamma}_U - \dot{\alpha}_U \qquad (2)$$

where, $\dot{\alpha}_U$ is the error of T_1 under voltage of U.

Step 3) $U_{T2}=2U$, $U_{T1}=U$, the primary voltage would be 2U, the error measured be the test set is denoted as .

$$\dot{\varepsilon}_3 = \frac{2\dot{U}(1 + \dot{\gamma}_{2U}) - \dot{U}(1 + \dot{\alpha}_U + \delta) - \dot{U}(1 + \dot{\beta}_U)}{2\dot{U}(1 + \dot{\gamma}_{2U})}$$
$$\approx \dot{\gamma}_{2U} - \frac{\dot{\alpha}_U + \dot{\delta} + \dot{\beta}_U}{2} \qquad (3)$$

where, $\dot{\gamma}_{2U}$ is the error of T_X under voltage of 2U.

From (1) to (3), it is indicates that the error variation of T_X between voltage U and 2U could be measured via the three steps described above, could be measured directly using a low voltage standard such as an inductive voltage divider, the error would be obtained. The added error resulted from the common mode voltage of the primary

winding of T1 is canceled via the calculation from (1) to (3).

The start point of this traceability system is 1 kV by using inductive voltage dividers with a maximum voltage of 1.5 kV. Its ratio errors at different settings are calibrated with a bootstrap method. In step 2, a 200 V multi- IVD is calibrated by the 1 kV IVD. In step 3, the 1 kV IVD and the 200 V multi-decade IVD, connected in cascade, is used as the standard to calibrate the 10 kV voltage transformer up to 15% of its rated primary voltage. In step 4, the measurement process described in part II would be carried out with two 5 kV special designed auxiliary voltage transformers to get the error variation between voltages of U and 2U. Then, the errors of the voltage range above 15 % would be calculated. In step 5, the 10 kV transformer and the 200V multi-decade IVD would be used as a standard in cascade to calibrate the voltage range up to 20% of 110 kV/√3 voltage transformer. Then the described HSS method measurement process would be repeated under different voltages up to 1.2×110kV/√3.

B. PTB Calibration System

The measurement system consists mainly on a calibrated standard voltage transformer (N), which serves as a reference, a self-calibrating voltage transformer bridge, based on the differential method in PTB [6] and the transformer under test (X). The bridge and the calibration circuit is shown in Fig 4.
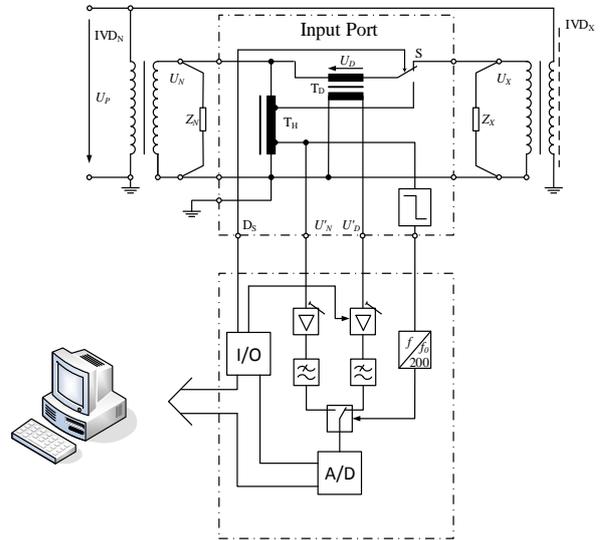

Fig. 4   voltage transformer calibration circuit of PTB

The measurands "ratio error" and "phase displacement" for voltage transformer calibration in the voltage range from 1 kV to 800 kV/√3 at 50 and 60 Hz are maintained in a 1000 V inductive voltage divider (IVD) and a set of six different standard VTs whose accuracy class is 0.02 or better. The traceability of the standard transformers is based on a fundamental step-up method using active capacitive high-voltage dividers [7].

IV. RESULTS AND DISCUSSIONS

A Transfer Standard Behaviour

NCHVM measured the voltage transformers two times before the voltage transformers was transited to PTB and after it was delivered back to NCHVM. Fig.5 and Fig. 6 shows the results for the measurements at test points varying from 20 % to 120% of the rated voltage at 50 Hz and at an ambient temperature of 23 °C ± 3 °C.
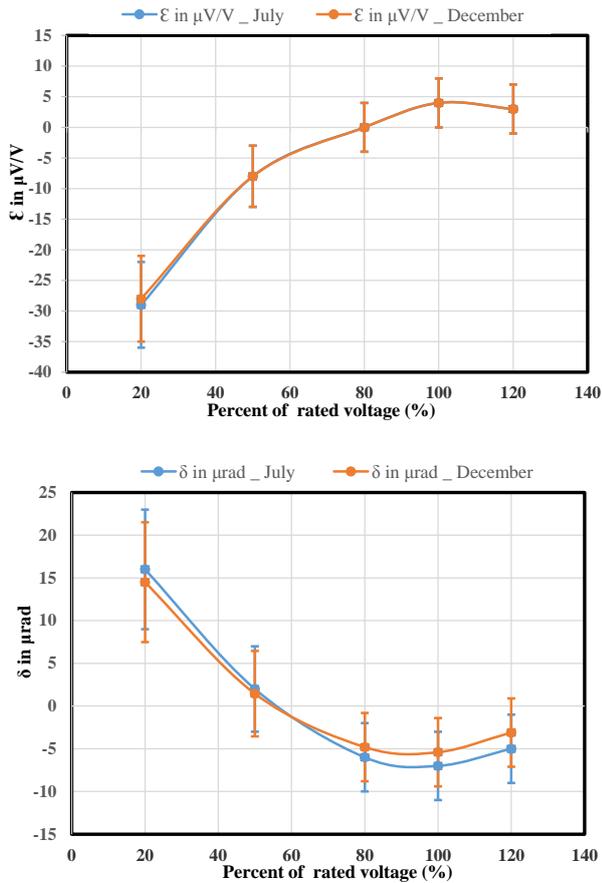
Fig. 5 Stability of the 10kV travelling standard ratios and phase displacements during July and December 2018

The stability of the 10kV travelling standard is estimated from difference of the two measurements is within ±1 ppm and ±2 μrad at the corresponding measurement points. The stability of the 110kV travelling standard is estimated in the same way and is within ±1 ppm and ± 2 μrad at the corresponding measurement points. The ±1 ppm and ± 2 μrad will be used as fixed uncertainty contributions $u_{Std}(\varepsilon)$ and $u_{Std}(\delta)$ for the travelling standards. Assuming a rectangular distribution, the uncertainty contributions are $u_{Std}(\varepsilon)= 1 / \sqrt{3} \approx 0.6$ ppm and $u_{Std}(\delta) = 2 / \sqrt{3} \approx 1.2$ μrad
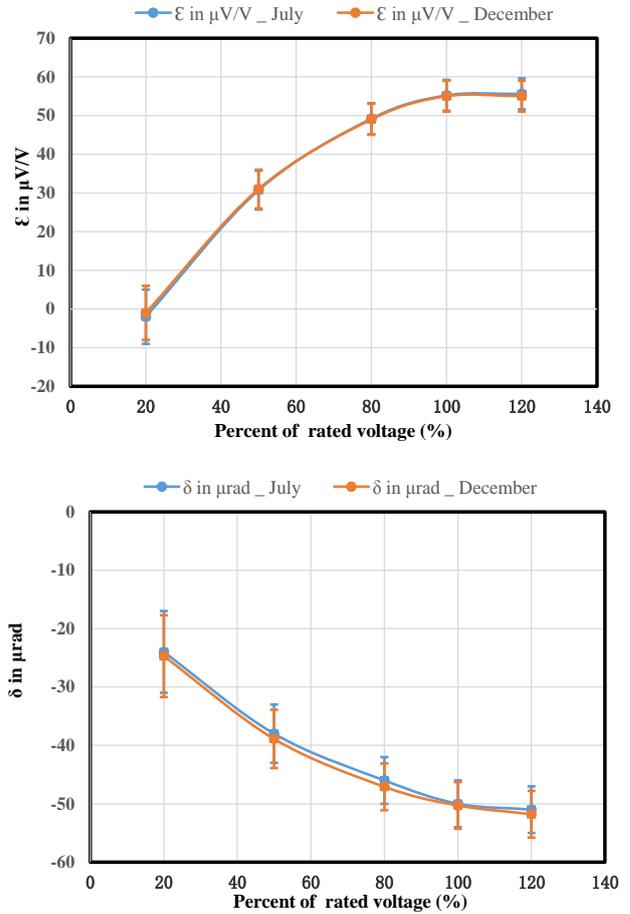

Fig. 6 Stability of the 110kV travelling standard ratios and phase displacements during July and December 2018

B Measurement Results Of PTB And NCHVM

The measurement results of PTB and NCHVM are shown Fig. 7 and Fig. 8. In table 1, the results as well as the expanded uncertainties U for $k = 2$ are given for all measurement results. The overall impression is, that the characteristical error course for the ratio and phase error is nicely resolved from both laboratories.
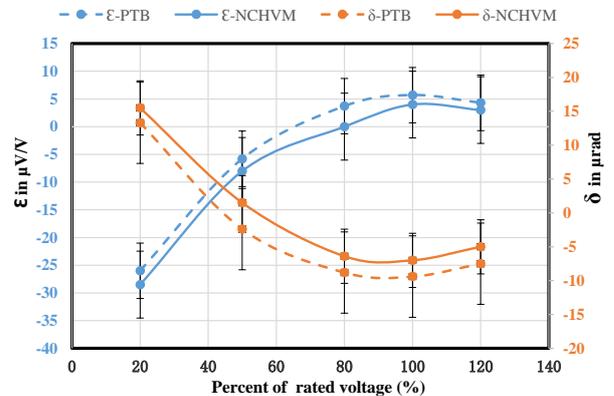

Fig.7 results of the measured error with 10kV travelling standard
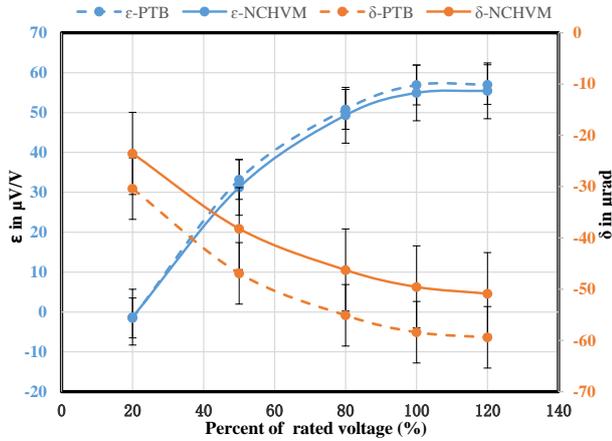
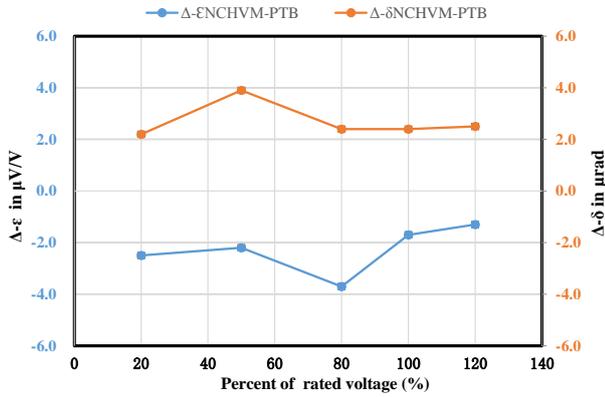Fig.8 results of the measured error with 110kV travelling standard

The detailed data for differences and EN factor of PTB and NCHVM as shown in the table 2, The 10kV and110kV travelling standards ratio error differences ($\Delta\varepsilon$) and phase displacement differences ($\Delta\delta$) are shown in the above of Fig.7 and Fig.8. The EN factor for the ratio error difference EN($\Delta\varepsilon i$) and for the phase displacement difference EN($\Delta\delta i$) are shown in the lower part of the Fig.9 and Fig.10.

Table 1   voltage transformer ratio error and phase error results of PTB and NCHVM

Frequency is 50 Hz			PTB results				NCHVM results			
K_n in V/V	U_p/U_{pn} in %	Z_b	ε_u in μV/V	δ_u in μrad	$U(\varepsilon)$ k=2 in ppm	$U(\delta)$ k=2 in μrad	ε_u in μV/V	δ_u in μrad	$U(\varepsilon)$ k=2 in ppm	$U(\delta)$ k=2 in μrad
10000/100	120	40kΩ	4.3	-7.5	4	5	3	-5.0	4	4
	100		5.7	-9.4	4	5	4	-7.0	4	4
	80		3.7	-8.8	4	5	0	-6.4	4	4
	50		-5.8	-2.4	4	5	-8	1.5	4	4
	20		-26.0	13.3	4	5	-28.5	15.5	4	4
$\dfrac{(110000/\sqrt{3})}{100}$	120	> 3MΩ	57.0	-59.4	4	5	55.4	-50.9	7	8
	100		56.9	-58.4	4	5	54.9	-49.6	7	8
	80		50.8	-55.1	4	5	49.3	-46.3	7	8
	50		33.2	-46.9	4	5	31.73	-38.2	7	8
	20		-1.5	-30.4	4	5	-1.3	-23.5	7	8

Table 2   Differences of the Voltage ratio error and of the phase displacement results of PTB NCHVM, and their EN factor.

| K_n in V/V	U_p/U_{pn} in %	Z_b	$\varepsilon_{NCHVM-PTB}$ in μV/V	$\delta_{NCHVN-PTB}$ in μrad	$U_C(\Delta\varepsilon)$ k=2 in μV/V	$U_C(\Delta\delta)$ k=2 in μrad	EN($\Delta\varepsilon$)	EN($\Delta\delta$)
10000/100	120	40kΩ	-1.3	2.5	5.8	6.8	-0.22	0.37
	100		-1.7	2.4	5.8	6.8	-0.29	0.35
	80		-3.7	2.5	5.8	6.8	-0.64	0.35
	50		-2.2	3.9	5.8	6.8	-0.38	0.58
	20		-2.5	2.2	5.8	6.8	-0.43	0.32
$\dfrac{(110000/\sqrt{3})}{100}$	120	> 3MΩ	-1.6	8.5	8.2	9.7	-0.19	0.88
	100		-2.0	8.8	8.2	9.7	-0.24	0.91
	80		-1.5	8.8	8.2	9.7	-0.18	0.91
	50		-2.0	8.7	8.2	9.7	-0.24	0.90
	20		0.2	6.9	8.2	9.7	0.03	0.71

(1) NCHVM-PTB differences
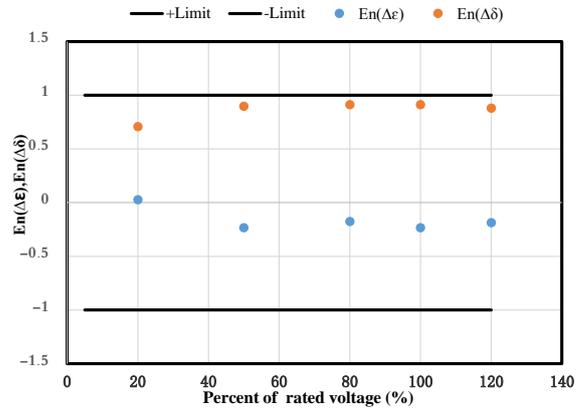
(2) EN factor

Fig.10 110kV travelling standard
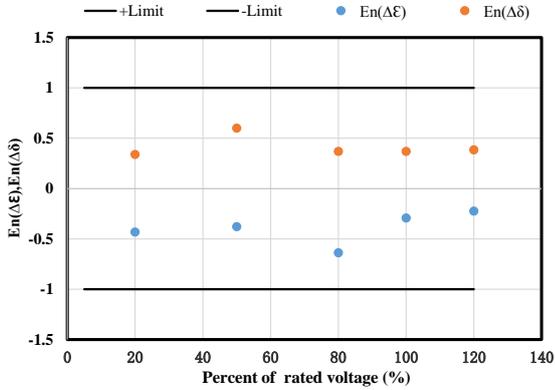
(2) EN factor

Fig.9 10kV travelling standard
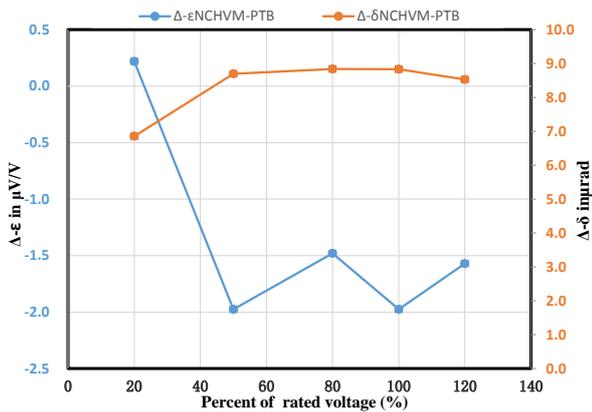
(1) NCHVM-PTB differences

V. CONCLUSIONS

The calibration results using the NCHVM system were based on the average of ten measurements at each test voltage. The voltage transformers was calibrated at test voltages of 20% up to 120% of rated. From these results it was found that the travelling standard has excellent repeatability characteristics within two ppm and four μrad. Since the calibration results are extensive, only some of the intercomparison results are shown. Fig. 7 and Fig.8 shows the differences between the calibration results of the voltage transformer travelling standard obtained using the NCHVM and PTB calibration systems for the 50 Hz. For the 10kV the differences varied considerably with the applied test voltage, but were less than 4 parts in 10^6 for the ratio and 4 μrad for the phase displacement. The 110kV were less than 2 ppm and 9 μrad.

It can be seen that both sets of measurements agree very well within the calculated measurement uncertainties. No outliers were observed. Considering especially the EN factors, the calculated uncertainties are reasonable.

VI. ACKNOWLEDGMENT

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