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COMPARISON OF VOLTAGE TRANSFORMER MEASURING SYSTEMS AT 110 KV AND 10 KV

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Abstract

A comparison of measurements of voltage transformer (VT) voltage ratio and phase displacement was performed between the National Center for High Voltage Measurement (NCHVM), China and the National Measurement Institute (NMI), Australia, with two voltage transformers provided by the NCHVM being used as the travelling standards. Voltage ratios of the 10 kV/100 V transformer measured by the two institutes differed by less than 5 µV/V and the phase displacement by less than 6 µrad, while voltage ratios of the $(110/\sqrt{3}$ kV)/100 V transformer differed by less than 16 µV/V and 13 µrad. These results confirmed that measurement results of the two institutes agreed within detailed measurement uncertainties evaluation. The comparison further enhances the confidence in both methods, which are widely used for calibration of voltage transformers in the electricity industry.

Keywords: voltage transformer, bilateral comparison, voltage transformer measuring system.

1. Introduction

In the comparison of high-voltage ratios between the *National Center for High Voltage Measurement* (NCHVM), China and the *National Measurement Institute* (NMI), Australia, The objective of the comparison is to verify whether, within the uncertainty of the measurements, there would be good agreement of the voltage transformer measuring systems performance characteristics [1, 2].

This VT embodying the German National Standard had been calibrated previously using the NCHVM inductive summation method. They were then sent to the NMI and were measured in November 2020 using the NMI measurement system based on absolute build-up methods using capacitive dividers. The measurements were performed at a frequency of 50 Hz. The accurate values for a voltage transformer are important for cross-border trade in electrical energy. Therefore, this intercomparison of VT calibration systems included calibration of the transfer standard at a test frequency of 50 Hz, which is the frequency used by the Chinese power system.

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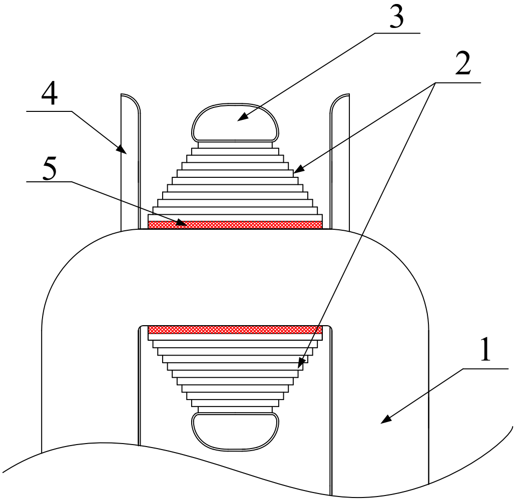
The NCHVM is committed to the research of the voltage transformer standard measuring device development setting standards in this field. Among these, a high precision *voltage transformer* (VT) was used as the transfer standard which independently developed by the NCHVM. The comparison has testified to satisfactory agreements of measurement results and this paper mainly introduces the comparison of voltage transformer measuring systems between China and Australia [3].

2. Transfer Standards

The 110/$\sqrt{3}$kV travelling standard has been independently developed by the NCHVM. The primary windings of this voltage transformer are similar to those in a traditional single-stage high-voltage VT [4,5], which are wound as a "pyramid" structure, as shown in Fig. 1. This winding method provides the top turns, which bear the highest voltage, sufficient insulation distance to the "ground shield". The method also enables a more uniform distribution of the electric field. The 110 kV VT was designed with error limits of 0.005% for the voltage error and 0.005 crad for the phase displacement, and the 10 kV VT with 0.01% and 0.01 crad. These error limits were for the operating voltages of 20% up to 120% of the rated voltage [6–8].

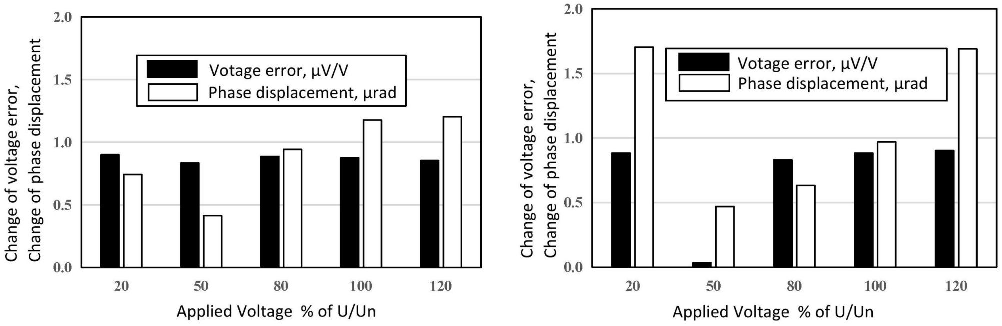


1. First-stage core 2. Excitation winding
3. Grading ring 4. Ground shield 5. Insulation skeleton

Fig. 1. Structure of the 110 kV high-voltage winding.

The NCHVM performed the measurements twice, once before delivering the transformer to the NMI in July 2020 and again after receiving it back from the NMI in January 2021. The stability of the travelling standards was estimated from the differences between the two sets of measurements, which were within ±0.9 µV/V and ±1.2 µrad for the 10 kV standard and within ±0.9 µV/V and ±1.7 µrad for the 110/$\sqrt{3}$ kV standard. The details are given in Fig. 2.

Since these changes were significantly lower than other components of measurement uncertainties, a corresponding common value of standard uncertainty for the stability of the travelling standard, $u_{\mathrm{STD}} = 1.9/\sqrt{3}$ µV/V (or µrad) ≈1.1 µV/V (or µrad) was used at all test points of the two travelling standards measured at the NCHVM.



(a) 10 kV standard

(b) 110 kV standard

Fig. 2. Changes inerrors for the travelling standards between July 2020 and January 2021.

3. Measurement Systems

3.1. NCHVM Measurement System

The principle of the NCHVM calibration system is shown in Fig. 3. It consists of a standard voltage transformer (VT_N), a voltage transformer under-test (VT_X), and a *voltage transformer test set* (VTTS) developed by NCHVM [9].

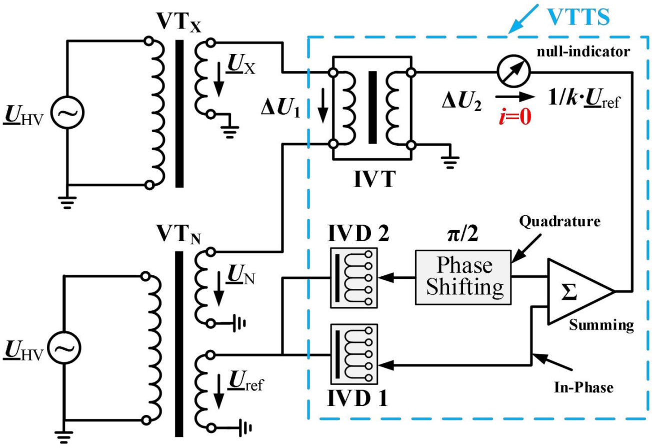


Fig. 3. The principle of the NCHVM measurement system.

The primary windings of the VT_X and the standard VT_N are connected to the same $\underline{\boldsymbol{U}}_{HV}$. The secondary windings of VT_X and VT_N($\underline{\boldsymbol{U}}_X$ and $\underline{\boldsymbol{U}}_N$) are grounded at their low voltage terminals. The difference between the high voltage terminals is compared to obtain the differential voltage ($\Delta\underline{\boldsymbol{U}}_1 = \underline{\boldsymbol{U}}_X - \underline{\boldsymbol{U}}_N$). After $\Delta\underline{\boldsymbol{U}}_1$ passes through an isolation voltage transformer (IVT) with a ratio of 1:1, it becomes ΔU_2 with reference to GND. For measuring the value of $\Delta\underline{\boldsymbol{U}}_2$, firstly, the VTTS acquires a reference voltage ($\underline{\boldsymbol{U}}_{ref}$) from the secondary of the VT_N. $\underline{\boldsymbol{U}}_{ref}$ is usually equal to the U_N (100 V or $100/\sqrt{3}$ V). Then, voltage $1/k\underline{\boldsymbol{U}}_{ref}$, which equals to $\Delta\underline{\boldsymbol{U}}_2$ in value but is opposite in phase, is constructed through multi-stage signal transformation [10, 11]. The null-indicator is used to reach the balance condition $1/k\underline{\boldsymbol{U}}_{ref} = -\Delta\underline{\boldsymbol{U}}_2$.

IVD 1 and IVD 2 are both inductive voltage dividers with a rated voltage of 100V. They are used to reduce the reference voltage $\underline{\boldsymbol{U}}_{\text{ref}}$ to a small fraction of $\underline{\boldsymbol{U}}_{\text{ref}}$ (in mV or even at the µV level). The output of IVD 1 is an in-phase component with reference to $\underline{\boldsymbol{U}}_{\text{ref}}$. The output of IVD 2 becomes a quadrature component after passing a 90-degree phase shifter. The in-phase and quadrature components are combined to obtain $1/k\underline{\boldsymbol{U}}_{\text{ref}}$ by using a summation amplifier.

If the ratios of IVD 1 and IVD 2 are k_1 and k_2, then we have

$$\Delta U_2 = -\frac{1}{k}U_{\text{ref}} = -\left(\frac{1}{k_1} + j\frac{1}{k_2}\right)U_{\text{ref}}, \tag{1}$$

and the complex error of the VTX can be expressed as

$$\varepsilon = \frac{\Delta U_1}{U_{\text{ref}}} \approx \frac{\Delta U_2}{U_{\text{ref}}} = -\left(\frac{1}{k_1} + j\frac{1}{k_2}\right). \tag{2}$$

The values of $1/k_1$ and $1/k_2$ are both in the range of 10^{-4} to 10^{-7}. By adjusting the values of k_1 and k_2, the null-indicator can be set to zero. With the indicated values of k_1 and k_2, the error of the VT_{X} can be calculated. The relative measurement error of the VTTS is less than 1%, relative to the measured ratio error and phase displacement. Even with the error level of 10^{-6}, the relative measurement error of the VTTS is still better than 5%.

The measurement uncertainty using the NCHVM calibration system is determined primarily by the uncertainty that can be achieved by the VTTS, and the stability of the standard VT_{N}. The 10 kV and $100/\sqrt{3}$ kV standard voltage transformers used in the NCHVM are two-stage precision VTs with high stability [12]. The expanded uncertainty for 10 kV is less than 4 µV/V for ratio error and 4 µrad for phase displacement at a frequency of 50 Hz. The expanded uncertainty for $110/\sqrt{3}$ kV is less than 7 µV/V for ratio error and 8 µrad for phase displacement at a frequency of 50 Hz [13].

3.2. NMI Measurement System

The NMI measurement system was based on the absolute build-up method (Clothier method) using capacitive dividers (Fig. 4).

At balance, $I_1 = I_2 + I_R$

$$j\omega C_{1N}\left(1 + a + j\alpha\right)V_P = j\omega C_{2N}\left(1 + c + j\gamma\right) + \frac{\lambda V_2}{R_{\mathrm{N}}\left(1 + d + j\delta\right)}, \tag{3}$$

where C_{1N}, C_{2N} and $R_{\mathrm{N}}$are the nominal values ofC_1, C_2 and R

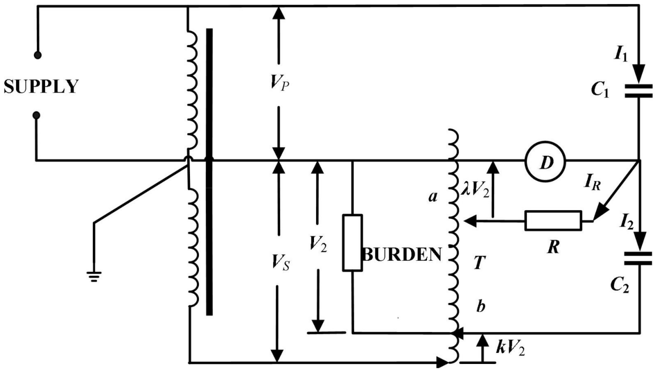
$$\frac{C_{1N}}{C_{2N}}\left(1 + a + j\alpha\right)V_P = \frac{V_S}{(1+k)}\left[1 + c + j\gamma - j\frac{\varphi}{1 + d + j\delta}\right], \tag{4}$$

where φ is the indicated phase error in radians

$$\varphi = \frac{\lambda}{\omega C_{2N} R_{\mathrm{N}}}. \tag{5}$$

In this testing set, $\boldsymbol{k} = v/10^6$ and $\lambda = pM/10^6$, where v and p are the readings on the voltage error and phase error dials respectively and M is the reading on the M dial. Also in this VT Testing Set, the value of R, and other circuit components are such that the following applies:

$$\varphi = \frac{500M}{C_2} \times \frac{50}{f} \times \frac{p}{10^6}, \tag{6}$$



V_P: primary voltage of VT under test; V_S: secondary voltage of VT under test; C_1: high-voltage arm capacitor; C_2: low-voltage arm capacitor; D: null detector; R: phase resistor; T: inductive voltage divider; b: for adjusting phase balance; a: for adjusting ratio balance

Fig. 4. Capacitive build-up method (Clothier method) applied by the NMI

$$\frac{V_S}{V_P} = \frac{C_{1N}\,(1 + a + j\alpha)\,(1 + k)}{C_{2N}\left[1 + c + j\gamma - j\dfrac{\varphi}{(1 + d + j\delta)}\right]}, \tag{7}$$

where $\boldsymbol{k}$ is the rated voltage transformation ratio, C_{1N}, C_{2N} and R_{N} are the nominal values of C_1, C_2 and R, $\boldsymbol{a} + \boldsymbol{j}\alpha$ the fractional correction to capacitance C_1, $\boldsymbol{c} + \boldsymbol{j}\gamma$ the fractional correction to capacitance C_2, $\boldsymbol{d} + \boldsymbol{j}\delta$ the fractional correction to resistance R, M the “Ratio Multiplier” dial reading on the testing set, p the phase-error dial reading on the testing set in μrad.

The fractional voltage error VE and phase displacement PD of the voltage transformer under test are determined by the following approximation formulae, which neglect 2nd and higher orders effects:

$$VE = \frac{kC_{1N}\left[1 + a + c + k - \dfrac{1}{2}\varphi^2 + ak\right]}{C_{2N}} - 1, \tag{8}$$

$$PD = \varphi - \alpha - \gamma, \tag{9}$$

$$\Phi = \frac{pM}{\omega C_{2N} R_{\mathrm{N}} 10^6}. \tag{10}$$

The voltage ratio of the divider formed by C_1 and C_2 was matched to the nominal ratio of the voltage transformer under test, the high-voltage arm capacitor C_1 was formed by a three-terminal compressed gas capacitor. One of the two nominal capacitance values, 50 pF and 5 pF, could be switched into the circuit to form C_1. Capacitor C_2 was formed by a combination of air-insulated low voltage capacitors.

The correction values of C_1 and C_2, both in-phase and quadrature components, were determined with the capacitor build-up procedure described in [14].

The nominal value of phase resistor R was 6.366 MΩ ($20/\pi$ MΩ), with its resistance value being determined with an uncertainty of 0.0007 MΩ and its susceptance confirmed as negligible using a precision capacitance bridge.

The standard uncertainties of measurements for the 10 kV transformer were $u(\varepsilon) = 3.0$ μV/V and $u(\delta) = 3.0$ μrad, and 7.5 μV/V and 5.5 μrad for the measurements of the $110/\sqrt{3}$ kV transformer.

4. Uncertainty Budgets

4.1. Uncertainty Budgets of NCHVM

Table 1. NCHVM uncertainty budget for the voltage ratio error and the phase displacement for 10 kV. The test points vary from 20% to 120% and the frequency is 50 Hz.

50 Hz Rate: Primary voltage – 10 kV, Secondary voltage – 100V, V/Vn = 20%–120%			
Voltage ratio error ε_x			
Source of uncertainty	Divisor	Type	$u_i(y)$, ppm
Uncertainty type A ($n = 10$)	1	A	0.43
1 kV inductive voltage divider	2	B	1.00
Test set	1.732	B	0.24
Influence of working electromagnetic field	1.732	B	1.16
Influence of external magnetic field	1.732	B	0.58
Influence of burden	1.732	B	0.34
Influence of the auxiliary VT	1.732	B	0.57
Combined standard uncertainty $u(\varepsilon_X) = 1.8$			
Round off – expanded measurement uncertainty ($k = 2$) U_{NCHVM} $(\varepsilon_x) = 4.0$			
Phase displacement δ_x			
Source of uncertainty	Divisor	Type	$u_i(y)$, µrad
Uncertainty type A ($n = 10$)	1	A	0.39
1 kV inductive voltage divider	2	B	1.00
Test set	1.732	B	0.24
Influence of working electromagnetic field	1.732	B	1.16
Influence of external magnetic field	1.732	B	0.58
Influence of burden	1.732	B	0.34
Influence of the auxiliary VT	1.732	B	0.57
Combined standard uncertainty $u(\delta_x) = 1.8$			
Round off – expanded measurement uncertainty ($k = 2$) U_{NCHVM} $(\delta_x) = 4.0$			

Table 2. NCHVM uncertainty budget for the current ratio error and the phase displacement for 110 kV. The test points vary from 20% to 120% and the frequency is 50 Hz.

50 Hz Rate: Primary voltage – 110 kV/$\sqrt{3}$, Secondary voltage – 100 V, V/Vn = 20%–120%			
Current ratio error ε_x			
Source of uncertainty	Divisor	Type	$u_i(y)$, ppm
Uncertainty type A ($n = 10$)	1	A	0.28
10 kV standard VT	2	B	1.5
Test set	1.732	B	0.48
Influence of working electromagnetic field	1.732	B	2.32
Influence of external magnetic field	1.732	B	1.16
Influence of the auxiliary VT	1.732	B	1.43

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Table 2 – *Continued from previous page*

50 Hz Rate: Primary voltage – 110 kV/$\sqrt{3}$, Secondary voltage – 100 V, V/Vn = 20%–120%			
Combined standard uncertainty $u(\varepsilon_x) = 3.4$			
Round off – expanded measurement uncertainty ($k = 2$) U_{NCHVM} $(\varepsilon_x) = 7.0$			
50 Hz Rate: Primary voltage – 110 kV/$\sqrt{3}$, Secondary voltage – 100 V, V/Vn = 20%–120%			
Phase displacement δ_x			
Source of uncertainty	Divisor	Type	$u_i(y)$, µrad
Uncertainty type A ($n = 10$)	1	A	0.35
10 kV standard T	2	B	1.5
Test set	1.732	B	0.60
Influence of working electromagnetic field	1.732	B	2.90
Influence of external magnetic field	1.732	B	1.45
Influence of the auxiliary VT	1.732	B	1.43
Combined standard uncertainty $u(\delta_x) = 4.0$			
Round off – expanded measurement uncertainty ($k = 2$) U_{NCHVM} $(\delta_x) = 8.0$			

4.2. Uncertainty Budgets of NMI

Table 3. NMI uncertainty budget for the voltage ratio error and the phase displacement for 10 kV. The test points vary from 20% to 120% and the frequency is 50 Hz.

50 Hz Rate primary voltage: 10 kV, secondary voltage: 100 V, V/Vn = 20%–120%			
Component	DOF	VE (ppm)	PE (urad)
		20	20
Capacitance divider build up		0.5	0.5
Short-term stability of capacitors	30	2.0	2.0
Add'. cap. Instability (upper arm)	2	0.3	0.3
Add'. cap. Instability (lower arm)	2	0.0	0.3
X5 and X50 test-set dials	inf	0.0	0.0
Test Set VE and PE dials	5	1.0	1.0
Voltage coefficient of capacitors	5	0.3	0.3
0.2% rated voltage	5	0.1	0.1
0.1% frequency	5	0.0	0.0
0.005 mS burden	5	0.6	0.3
1°C temperature	5	0.1	0.0
Reversal	inf	1.0	1.0
Phase-to-phase connections	inf	0.0	0.0
Instability	2	0.0	0.0
Rounding of reported error value	inf	0.3	0.3

Continued on next page

Table 3 – *Continued from previous page*

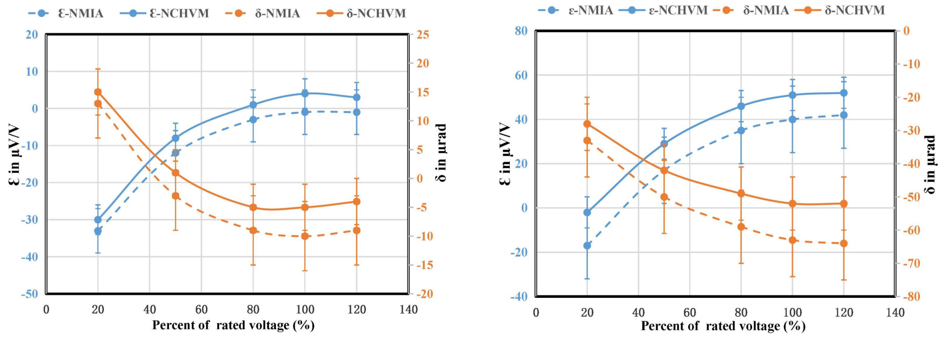
50 Hz Rate primary voltage: 10 kV, **secondary voltage: 100 V, V/Vn = 20%–120%**			
Rounding of reported uncertainty	inf	0.3	0.3
Rounding of coverage factor	inf	0.1	0.1
RSS of 1 to 15		2.7	2.6
Effective degrees of freedom		64.05	4-1 62.22
Coverage factor		2.000	2.001
Reported Coverage Factor		2.0	2.0
Expanded Uncertainty (%, crad)		0.00053	0.00052
Reported Uncertainty (%, crad)		0.0006	0.0006

Table 4. NMI uncertainty budget for the voltage ratio error and the phase displacement for 10 kV. The test points vary from 20% to 120% and the frequency is 50 Hz.

50 Hz Rate primary voltage: 10 kV, **secondary voltage: 100 V, V/Vn = 20%–120%**			
Component	DOF	VE (ppm)	PE (urad)
		20	20
Capacitance divider build up		0.5	0.5
Short-term stability of capacitors	30	2.0	2.0
Add’. cap. Instability (upper arm)	2	0.3	0.3
Add’. cap. Instability (lower arm)	2	0.0	0.3
X5 and X50 test-set dials	inf	0.0	0.0
Test Set VE and PE dials	5	1.0	1.0
Voltage coefficient of capacitors	5	0.3	0.3
0.2% rated voltage	5	0.1	0.1
0.1% frequency	5	0.0	0.0
0.005 mS burden	5	0.6	0.3
1°C temperature	5	0.1	0.0
Reversal	inf	1.0	1.0
Phase-to-phase connections	inf	0.0	0.0
Instability	2	0.0	0.0
Rounding of reported error value	inf	0.3	0.3
Rounding of reported uncertainty	inf	0.3	0.3
Rounding of coverage factor	inf	0.1	0.1
RSS of 1 to 15		2.7	2.6
Effective degrees of freedom		64.05	62.22
Coverage factor		2.000	2.001
Reported Coverage Factor		2.0	2.0
Expanded Uncertainty (%, crad)		0.00053	0.00052
Reported Uncertainty (%, crad)		0.0006	0.0006

5. Measurement Results

The measurements at the two institutes were performed at the same nominal voltages, from 20% up to 120% of the rated voltage of each of the travelling standards, at a frequency of 50 Hz and ambient temperatures of (23 ± 3)°C. The measurement results are shown in Fig. 5 and 6, with error bars representing the expanded measurement uncertainties.

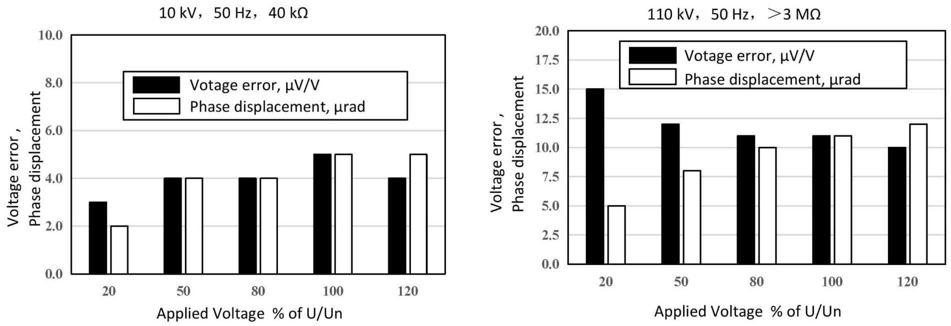


(a) 10 kV standard

(b) 110 kV standard

Fig. 5. Measured ratio errors and phase displacement values of the travelling standard.

Figure 6 shows the differences between the calibration results of the transfer standard VT obtained using the NCHVM and NMI calibration systems with a resistive burden of 40 kΩ for the measurement of the 10 kV VT and > 3 MΩ for the measurement of the $110/\sqrt{3}$ kV VT. The differences in relative voltage error and phase displacement between the NCHVM and the NMI systems are depicted in Fig. 6.



(a) (10 kV)/(100/ V), 50 Hz, 40 kΩ burden

(b) $(110/\sqrt{3}$ kV)/(100V), 50 Hz, 3 MΩ burden

Fig. 6. Differences between NCHVM and NMI results in relative voltage error and phase displacement at a) (10 kV)/(100/ V), 50 Hz, 40 kΩ burden; b) $(110/\sqrt{3}$ kV)/(100V), 50 Hz, 3 MΩ burden.

It can be seen that the maximum differences in results for the 10 kV measurement between the two institutes were 5 μV/V for the voltage error and 5 μrad for the phase displacement. From the measured differences, the respective measurement uncertainties for the two institutes and the stability values of the travelling standards, the maximum EN (normalized deviation) value obtained was 0.68 for all test voltages for the 10 kV transformer.

The maximum differences between the two institutes for the measurements of the $110/\sqrt{3}$ kV transformer were 15 μV/V and 12 μrad, which resulted in a maximum EN value of 0.90 for all test voltages.

6. Conclusions

The comparison results indicate that the measurements performed by the NCHVM and the NMI agreed within the estimated measurement uncertainties. No outliers were observed.

The measurement systems used in the comparison at the two institutes were based on completely different principles. The NCHVM system was a self-developed system based on the current comparator principle, while the NMI system was an absolute capacitive divider build-up method developed by the NMI. It was the first time that a comparison of voltage transformer measurements using these two methods has achieved satisfactory agreements of measurement results. These results further enhance the confidence in the measurement systems based on the principle of current comparators and the principle of capacitive divider built-up method.

Considering that the EN factor reached 0.90 for the ratio $(110/\sqrt{3}\ )/100$ V, there could be certain systematic effects that had not been accounted for in the measurements. Further investigation of possible systematic effects is desirable for achieving lower measurement uncertainties

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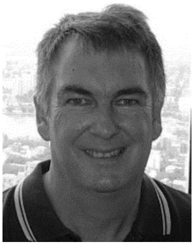

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