Metrol. Meas. Syst., Vol. 29 (2022), No. 2
DOI: 10.24425/mms.2022.140035

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METROLOGY AND MEASUREMENT SYSTEMS

Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

M&MS

AN IMPROVED ALGORITHM FOR THE SERIES STEP-UP METHOD BASED ON A LINEAR THREE-PORTS NETWORK

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Abstract

Capacitive leakage and adjacent interference are the main influence sources of the measuring error in the traditional series step-up method. To solve the two problems, a new algorithm was proposed in this study based on a three-ports network. Considering the two influences, it has been proved that response of this three-ports network still has characteristics of linear superposition with this new algorithm. In this three-port network, the auxiliary series voltage transformers use a two-stage structure that can further decrease measurement uncertainty. The measurement uncertainty of this proposed method at 500/√3 kV is 6.8 ppm for ratio error and 7 μrad for phase displacement (k=2). This new method has also been verified by comparing its results with measurement results of the PTB in Germany over the same 110/√3 kV standard voltage transformer. According to test results, the error between the two methods was less than 2.7 ppm for ratio error and 2.9 μrad for phase displacement.

Keywords: voltage transformer, traceability method, calibration, high voltage.

1. Introduction

Standard voltage transformers for power frequency usually contain a series *voltage transformers* (VTs) with different voltage classes (1 kV, 10 kV, 110/$\sqrt{3}$ kV, 220/$\sqrt{3}$ kV, 500/$\sqrt{3}$ kV and 1000/$\sqrt{3}$ kV). Among them, the 1 kV *inductive voltage divider* (IVD) applies self-calibration with the reference potential method [1-3] and its uncertainty can reach 10^{-7}. For 10 kV or higher standard VTs, error calibration is accomplished in two steps: (I) At 10% - 20% rated voltage points, error calibration is realized by the standard VT with lower voltage directly. (II) Error changes at the voltages from N% to 2N% rated voltage (called the voltage coefficient) were measured with the “step-up method”. Error under 20%-120% rated voltage could be gained by applying Step I once and multiple Step II.

The capacitor voltage coefficient method is one of the step-up methods. It is based on the low voltage coefficient of the standard capacitor. The uncertainty for this method is 8 ppm and 8 μrad (k=2) at 400/√3 kV for 50 Hz [4]. Reference [5] describes an experimental voltage divider circuit with the auto-calibration function during normal operation of the divider in the place of its installation. Reference [6] presents a self-calibration method for voltage dividers as well as the results of experimental and simulation studies, a version with single compensation when the voltage is lowered to 230 Vrms.

The series step-up method is another one that provides an opportunity for verification of the capacitor voltage coefficient method. The series step-up method was proposed by scholars from the *Physikalisch-Technische Bundesanstalt* (PTB, Germany) [7]. The voltage level of

Article history: received December 28, 2021; revised February 19, 2022; accepted March 3, 2022; available online April 27, 2022.

that series step-up method at that time can reach 35 kV and the measurement uncertainty is 12 ppm and 35 μrad. Later, it was improved in the 1990s [8-10] for easier operation and higher measurement accuracy. The voltage level of the improved series step-up method can reach $110/\sqrt{3}$ kV and the measurement uncertainty are 10 ppm and 10 μrad.

Reference [11] presents a further improved method which is applied to higher voltage with adding an isolation transformer. The uncertainty for this method is 3 ppm and 2.6 μrad (k=2) at $110/\sqrt{3}$ kV. But based on the reference, for $1000/\sqrt{3}$ kV, the uncertainty increases to 50 ppm and 50 μrad.

Recently, $500/\sqrt{3}$ kV two-stage VTs have been developed whose accuracy class can reach 0.002 [12]. To attain such a high accuracy standard VT, the measurement uncertainty of this series method in reference [11] needs to be improved.

2. The Error Caused by VT series connection

2.1. Two Influences of VT in Series

1) Capacitive leakage error. To analyze the capacitive leakage error, the equivalent circuit of distributed capacitance is shown in Fig. 1. Point B is the intermediate potential of the primary side, b and d are the intermediate potentials of the secondary side. E_{T1} is the potential of point B, and E_{T3} is the potential of points b and d. Due to the existence of distributed capacitances C_1, C_2, C_3, leakage current I_{c1}, I_{c2}, I_{c3} will be formed. Considering that current I_{c1} is directly driven by the power supply U_{11} and does not flow through the primary winding of VT, the resulting error ε_1 can be ignored. The current I_{c2} flows through the isolation transformer T_2. The secondary winding of T_2 will produce a voltage drop on the internal impedance Z_2 of the winding, which will cause additional series errors ε_2. Error ε_3 is similar to ε_2.

In addition, there is an inherent potential difference U between the primary winding and the secondary winding of the isolated VT T_2. The capacitive current I_{c4} caused by the distributed capacitance C_4 will also bring additional error ε_4. Due to the small distance between the primary winding and the secondary winding of T_2, the capacitance of C_4 is larger. The small impedance of C_4 leads to a large current I_{c4}. Therefore, ε_4 is the main source of capacitive leakage error.

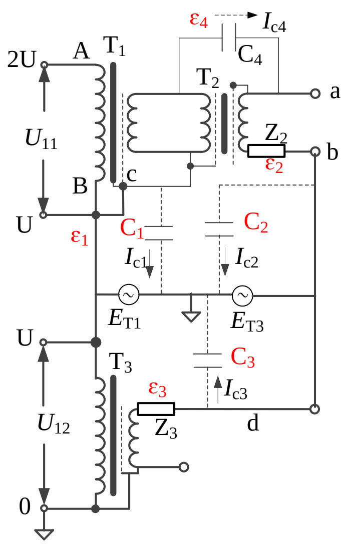


Fig. 1. Equivalent circuit of distributed capacitance.

DOI: 10.24425/mms.2022.140035

2) Adjacent interference. Adjacent interference also affects the measuring accuracy of the series step-up method. Under high voltage, adjacent interference must be taken into account when two voltage transformers are connected in series (also including measurement interference produced by the connecting wire between the transformers). In the series step-up method, the test circuit has to be changed, so the relative position of the devices and the connection pattern of the wires change accordingly. Theoretically, these produce different adjacent interference and measurement error which generally cannot be ignored in the measurement process.

2.2. The Measurement of the Capacitive Leakage and Adjacent Interference

1) Next, the influence of the two influences above should be measured. The measurement principle is shown in Fig. 2. Figure 2(a) shows the principle of measuring the error of the upper-level VT T_1 and T_2, written as $\varepsilon_{a,\text{ and}}$. Figure 2(b) shows the error measurement for the lower-level VT T_3, written as ε_b.

Take Fig. 2(a) as an example to illustrate the measurement method: short-circuit the primary winding of T_1 (the potentials of the A and B terminals are equal, U). If the two influences are ignored, the output voltage of the upper-level VT T_1 is ΔU=0. Then the actual measurement of the output voltage is the additional error ε_a caused by the series transformer. During the test, the output terminal U_{ref} of the lower voltage transformer T_3 is the reference voltage. The test results are shown in Table 1.

(a) Error of T_1 and T_2 (b) Error of T_3

Fig. 2. Principle of the measurement.

Table 1. Measurement results for influences of capacitive leakage error and adjacent interference. The rated voltage of T_1 and T_3 is 250 kV/$\sqrt{3}$.

	Applied voltage Un (%)	15	30	60
εa	**Ratio error in ppm**	14.3	14.8	16.5
	Phase displacement in µrad	-10.2	-10.5	-12.2
εb	**Ratio error in ppm**	4.2	4.3	4.2
	Phase displacement in µrad	-3.4	-4.0	-3.8

Considering the influences presented above, a new algorithm for the series step-up method was proposed in this study.

3. Principle of the three-ports network

A linear three-ports network is shown in Fig. 3. It has two input ports (A_1—X_1 and A_2—X_2) and one output port a-x. This network is composed of linear passive devices, such as a resistor, a capacitor, and a reactor. According to the circuit principle, the current equations contained in this network could be set up by all current circuits. Since all components are linear, these circuit equations must be linear and the solution of branch current is linear. Hence, the solution of the circuit equation of the three-ports network can be expressed as:

$$[\dot{I}] = [Y][\dot{U}], \tag{1}$$

Where $[\dot{I}]$ and $[\dot{U}]$ are column vectors. The three-ports network only has two input ports. The accessed excitation voltages are set $\dot{U}_1$ and $\dot{U}_2$. Hence, the corresponding column vector $[\dot{U}]$ has only two non-zero elements. The response of this three-ports network is:

$$\dot{U}_3 = \sum_{m,n} Z_m \dot{I}_n \,, \tag{2}$$

where $\dot{U}_3$ is the output voltage at a-x, Z_m is impedance in a circuit branch which is connected to a-x of the network and $\dot{I}_n$ is the current in the chosen current branch. Since Z_m in this network is linear, the responses of a-x to $\dot{U}_1$ and $\dot{U}_2$ have proportionality and superposition.

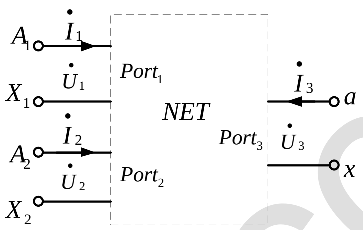


Fig. 3. Linear three-ports network.

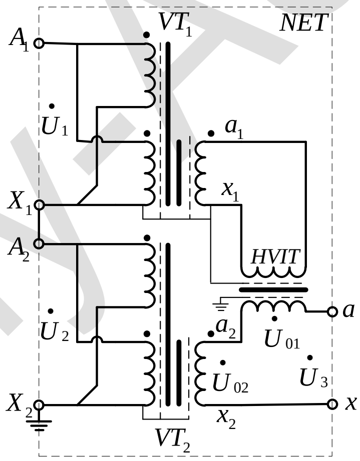
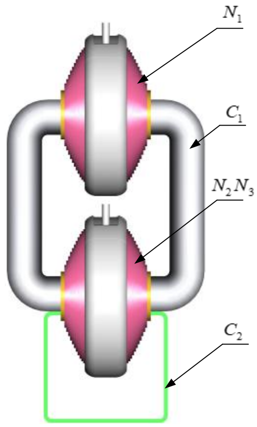


Fig. 4. Internal structure of the linear three-ports network.

To implement the series step-up method in such a linear three-ports network, the network structure from Fig. 4 could be applied. In this three-ports network, the ground-connected voltage transformers (VT_1 and VT_2) and the *high-voltage isolated transformer* (HVIT) were used as network devices.

In Fig. 4, VT_1 and VT_2 are both two-stage voltage transformers. The structure of the two-stage VT is shown in Fig. 5 [10]. The error of the two-stage VT for 110kV to 500 kV is less than 0.002%. Moreover, the low voltage coefficient is an important characteristic of the two-stage VT. The structure of the HVIT is detailed in reference [13].



C_1: first-stage core C_2: second-stage core
N_1: first-stage winding N_2 and N_3: second-stage winding
Fig. 5. Structure of a two-stage voltage transformer for high voltage

If these voltage transformers are linear passive devices, the circuit equation and admittance matrix [Y] could be listed, and the network response is calculated by the solving method for the linear network. This implies that this network has proportionality and superposition. The output variables of the network are $\dot{U}_{01}$ and $\dot{U}_{02}$. According to the linear hypothesis, there is:

$$\dot{U}_{01} = m\dot{U}_1 + g\dot{U}_2 + h\dot{U}_2\,, \tag{3}$$

where *m*, *g*, and h are proportional constants, $m\dot{U}_1$ is the voltage when the input voltage $\dot{U}_1$ is transmitted to the output port after cascade connection of VT_1 and HVIT, $g\dot{U}_2$ is the disturbance voltage that is produced at the output end when the primary voltage $\dot{U}_2$ is applied, and $h\dot{U}_2$ is the leakage voltage at the output end when the voltage $\dot{U}_2$ is applied between the primary and secondary windings of HVIT.

Similarly, it can be obtained that:

$$\dot{U}_{02} = n\dot{U}_2 + f\dot{U}_1\,. \tag{4}$$

where n and f are proportional constants, $n\dot{U}_2$ is the voltage which is the transmitted component of the primary voltage $\dot{U}_2$ to the output port by VT_2, and $f\dot{U}_1$ is the disturbance voltage at the output port when VT_1 applies the primary voltage $\dot{U}_1$.

In fact, the excitation impedance of the iron core of transformers is nonlinear. However, the voltage transformer is always designed to operate in a linear area, so the branch voltage still can be gained through superposition and the voltage at the output port ($\dot{U}_3$) also can be gained from superposition.

If the rated voltage ratio and ratio error after the cascade connection of VT_1 and HVIT are *K* and *α*, and the rated voltage ratio and ratio error of VT_2 are *K* and *β*, (3) and (4) can be further expressed as:

$$\dot{U}_{01} = \frac{\dot{U}_1}{K}(1+\alpha) + (g+h)\dot{U}_2 \tag{5}$$

$$\dot{U}_{02} = \frac{\dot{U}_2}{K}(1+\beta) + f\dot{U}_1 \tag{6}$$

If the rated voltage ratio of the standard voltage transformer VT_3 is also *K*, the ratio error is the function of input voltage, that is $\gamma(\dot{U})$. In this study, the new step-up method can be divided into three steps:

Step 1: The major departure from the traditional method, as shown in Fig. 6, is the application a booster transformer T_B. The voltage (-U) is applied at A_1-X_1, and voltage U is applied simultaneously at A_2-X_2 and VT_3. In this case, the network output is the influence of shielding leakage and adjacent interference. And it is a very low voltage (similar to difference voltage △U in normal operation conditions), but not equal to zero. The input potential difference of the test set is △U (a-x). At this moment, the measured value of the test set is ε_1 (△U / U_{ref}) and the ratio error of VT_3 is $\gamma(\dot{U})$. According to the definition of error of the transformer, the network output ($\dot{U}_{31}$) can be expressed as:

$$\dot{U}_{31} = \frac{\dot{U}}{K}[1+\gamma(\dot{U})]\varepsilon_1 \approx \frac{\dot{U}}{K}\varepsilon_1 \tag{7}$$

In result, it can be gained from the voltage balance of the network that:

$$\begin{aligned}\dot{U}_{31} &= \dot{U}_{01} + \dot{U}_{02} \\ &= -\frac{\dot{U}}{K}(1+\alpha) + (g+h-f)\dot{U} + \frac{\dot{U}}{K}(1+\beta)\end{aligned} \tag{8}$$

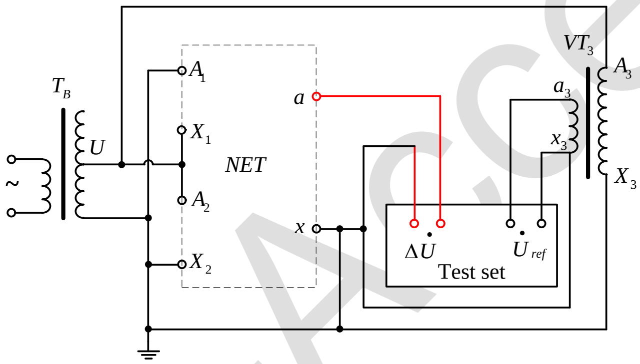


Fig. 6. Measurement of output response to the input port A_2-X_2.

Step 2: In Fig. 7, U is applied to A_1-X_1 and VT_3 simultaneously, while zero voltage (short circuit of two terminals) is applied at A_2-X_2. The potential difference △U (a-a_3) is accessed to the test set. a_3-x_3 is the secondary output port of VT_3 and a-x is the output of the network. Under this circumstance, the measured value of the test set is ε_2 and the ratio error of VT_3 is $\gamma(\dot{U})$. Therefore, the output ($\dot{U}_{32}$) of the network can be expressed as:

$$\dot{U}_{32} = \frac{\dot{U}}{K}[1+\gamma(\dot{U})](1+\varepsilon_2) \approx \frac{\dot{U}}{K}[1+\gamma(\dot{U})+\varepsilon_2] \tag{9}$$

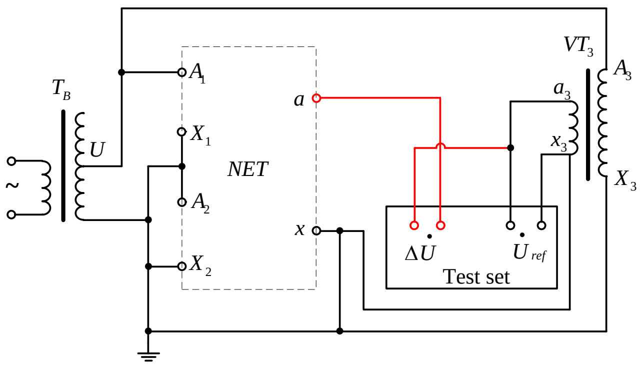


Fig. 7. Measurement of output response to the input port A_1-X_1.

DOI: 10.24425/mms.2022.140035

Similarly to (8), $\dot{U}_{32}$ is expressed as:

$$\dot{U}_{32} = \dot{U}_{01} + \dot{U}_{02} = \frac{\dot{U}}{K}(1+\alpha) + f\dot{U} \tag{10}$$

Step 3: In Fig. 8, the voltage U is applied simultaneously to A_1-X_1 and A_2-X_2 which are connected in series, while 2U is applied simultaneously at the primary side of VT_3. The potential difference △U (a-a_3) is accessed to the test set. The measured value of the test set is ε_3. Under this circumstance, the ratio error of VT_3 is $\gamma(2\dot{U})$. The network output $\dot{U}_{33}$ can be expressed as:

$$\dot{U}_{33} = \frac{2\dot{U}}{K}[1+\gamma(2\dot{U})](1+\varepsilon_3) \approx \frac{2\dot{U}}{K}[1+\gamma(2\dot{U})+\varepsilon_3] \tag{11}$$

Similarly to (8) and (10), $\dot{U}_{33}$ is expressed as:

$$\begin{aligned}\dot{U}_{33} &= \dot{U}_{01} + \dot{U}_{02} \\ &= \frac{\dot{U}}{K}(1+\alpha) + (g+h+f)\dot{U} + \frac{\dot{U}}{K}(1+\beta)\end{aligned} \tag{12}$$

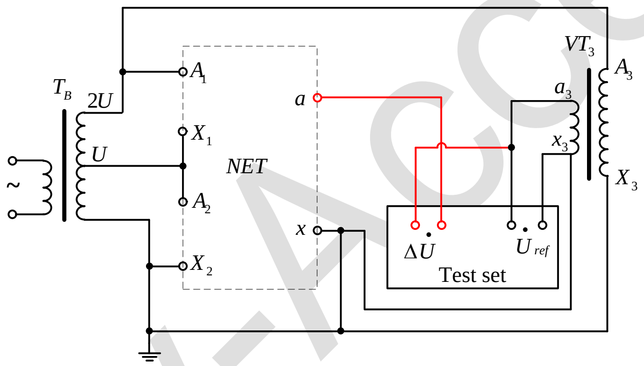


Fig. 8. Measurement of output responses to the input ports A_1-X_1 and A_2-X_2

Formula derivation is carried out after the three steps above. It can be gained from (8) and (10):

$$\begin{aligned}&\dot{U}_{31} + 2\dot{U}_{32} \\ &= -\frac{\dot{U}}{K}(1+\alpha) + (g+h-f)\dot{U} + \frac{\dot{U}}{K}(1+\beta) + 2\frac{\dot{U}}{K}(1+\alpha) + 2f\dot{U} \\ &= \frac{\dot{U}}{K}(1+\alpha) + (g+h+f)\dot{U} + \frac{\dot{U}}{K}(1+\beta)\end{aligned} \tag{13}$$

It can be gained through a comparison of (12) and (13) that:

$$\dot{U}_{31} + 2\dot{U}_{32} = \dot{U}_{33} \tag{14}$$

Combined (7), (9) and (11), (14) can be rewritten, so there is:

$$\frac{\dot{U}}{K}\varepsilon_1 + \frac{2\dot{U}}{K}[1+\gamma(\dot{U})+\varepsilon_2] = \frac{2\dot{U}}{K}[1+\gamma(2\dot{U})+\varepsilon_3] \tag{15}$$

Finally, (15) can be deduced to:

$$\gamma(2\dot{U}) - \gamma(\dot{U}) = \frac{\varepsilon_1}{2} + \varepsilon_2 - \varepsilon_3 \tag{16}$$

The error of VT_3 at the voltage point of U was measured by the calibration method directly (by using a standard voltage transformer with a lower-rated voltage but higher accuracy). Error coefficient of VT_3 when voltage increases from U to 2U could be calculated through (16). By repeating the process above, the error of VT_3 under 2^k U (k=1,2...) could be determined.

4. Measurement Uncertainty Analysis

The measurement uncertainty of this series step-up method varies with different voltage levels. We take $500/\sqrt{3}$ kV as an example. 20% to 50% of rated voltage can be calibrated directly with a $220/\sqrt{3}$ kV standard VT. And 60%, 80%, 100%, 120% of rated voltage can be calculated with the step-up method from 30%, 40%, 50% of rated voltage respectively. It does not need curve fitting. The main uncertain component consists of the following parts:

1) Type A measurement uncertainty. It is mainly caused by the noise in the measurements and the repeatability over several days.

$$U_{f1} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} u_{f1}^2} = 1\times10^{-6} \tag{17}$$

$$U_{\delta 1} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} u_{\delta 1}^2} = 1.2\mu rad \tag{18}$$

2) A $220/\sqrt{3}$ kV Standard VT. For a $500/\sqrt{3}$ kV standard VT, the error under 20%~50% of rated voltage is calibrated with a $220/\sqrt{3}$ kV standard VT with an accuracy class of 0.002. The measurement uncertainty u_{f2} and $u_{\delta 2}$ are 6×10^{-6} and 6 μrad (k=2) respectively.
3) Test set measurement unit. The measurement uncertainty would not be more than $0.1\varepsilon_m/\sqrt{3}$, where ε_m is the largest error of a series VT from 20% to 120% of the rated voltage. To calibrate a $500/\sqrt{3}$ kV VT, we should use two $250/\sqrt{3}$ kV in series with an accuracy class of 0.002. ε_m is 20 ppm and 20μrad. Therefore, u_{f3} and $u_{\delta 3}$ are 1.15×10^{-6} and 1.15 μrad respectively.
4) Surrounding uncertainty. Although adjacent interference is already considered in this paper, the surrounding uncertainty such as electromagnetic interference from the power supply and other surroundings should be calculated. This would be below 0.01εm, and is considered as a Gaussian distribution. Therefore, the measurement uncertainty u_{f4} and $u_{\delta 4}$ are 0.2×10^{-6} and 0.2 μrad respectively.
5) Remaining parts of compensation for shield leakage and adjacent interference. Usually compensation will never be perfect soan estimate should be added to the final uncertainty. The largest influence is 0.5×10^{-6} and 1 μrad, and as such it could be considered as uniform distribution so the measurement uncertainty u_5 would be divided by $\sqrt{3}$. Therefore, u_{f5} and $u_{\delta 5}$ are 0.3×10^{-6} and 0.6 μrad respectively.

And there may be additional factors in the complete system affecting the total measurement uncertainty. But we believe that it has a very small influence. As the above-mentioned components are independent of each other, so the expanded combined relative uncertainty would be:

$$U_f = 2\times\sqrt{\sum_{i=1}^{5} u_i^2} = 6.8\times10^{-6}, (k=2) \tag{19}$$

$$U_{\delta} = 2\times\sqrt{\sum_{i=1}^{5} u_i^2} = 7\ \mu rad, (k=2) \tag{20}$$

5. Experiment and Results

5.1. Comparison with PTB under 110/$\sqrt{3}$ kV

A 110/$\sqrt{3}$ kV voltage transformer (VT_3) with an accuracy class of 0.01 was used as the testing equipment. Measurement results of the proposed series step-up method and PTB were compared.

Method #1: At voltage points of 15% and 20% rated voltage 110/$\sqrt{3}$ kV, the voltage transformer was calibrated directly by a 10 kV two-stage voltage transformer with an accuracy class of 0.001. Measurement results are shown in Table 2. Next, the error of VT_3 in the range of 20% ~ 120% rated voltage was measured with the proposed series step-up method. Measurement data in Step 1 to Step 3 are listed in Table 3 where (A) is ratio error and (B) is phase displacement. Taking the measurement results in Table 3, (16) is applied to the calculation. Combining with data in Table 2, errors of VT_3 at five voltage points (30%, 40%, 60%, 80% and 120% of rated voltage) could be gained. Then, errors at points 50% and 100% of rated voltage could be gained via the curve fitting method.

Method #2: PTB's results based on active capacitive high voltage divider are also presented. The measurement uncertainty of this method is 2 ppm for ratio error and 2 μrad for phase displacement [14]. The final comparison of the two methods is shown in Fig. 9.

Table 2. Direct calibration results at low-voltage.

Applied voltage (%)	***f*** **in ppm**	***δ*** **in μrad**
15	-5.5	-26.0
20	0.9	-27.5

Table 3. Data of new series method.

(a) Ratio error

Applied voltage (%)	**ε1 in ppm**	**Applied voltage (%)**	**ε2 in ppm**	**ε3 in ppm**
20	-59.4	10	29.6	-16.6
30	-61.0	15	32.3	-19.5
40	-60.3	20	33.4	-21.5
50	-59.9	25	33.3	-22.7
60	-57.7	30	32.1	-24.4
70	-55.8	35	30.5	-24.4
80	-53.6	40	28.7	-24.6
90	-52.7	45	26.7	-24.4
100	-52.6	50	25.2	-23.4
110	-50.0	55	22.5	-21.8
120	-49.9	60	20.3	-18.3

(b) Phase displacement

Applied voltage (%)	**ε1 in μrad**	**Applied voltage (%)**	**ε2 in μrad**	**ε3 in μrad**
20	19.7	10	26.4	43.8
30	24.5	15	17.6	41.2
40	26.9	20	13.1	39.1

50	27.4	25	10.3	36.5
60	29.2	30	8.0	34.5
70	29.1	35	6.5	33.1
80	29.4	40	5.1	31.9
90	28.5	45	4.2	30.7
100	27.8	50	3.7	29.6
110	27.9	55	3.6	28.5
120	27.3	60	4.4	26.2

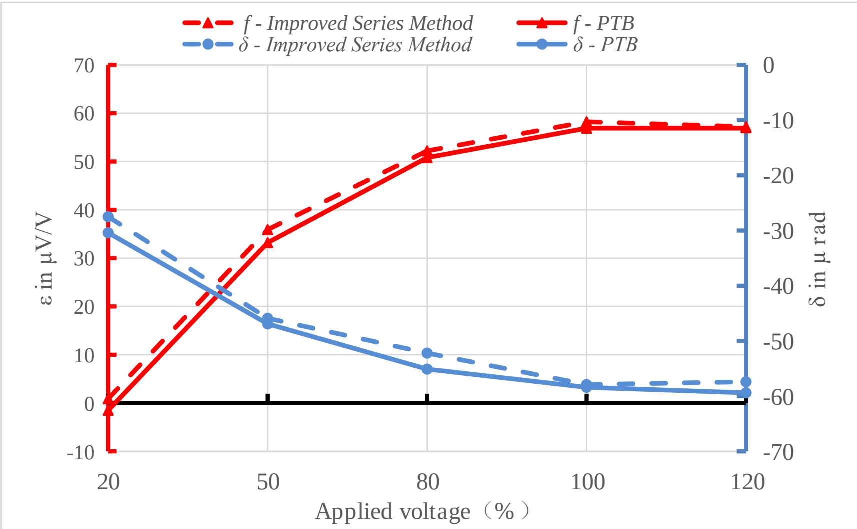


Fig. 9. Comparison of results with PTB.

It can be seen from Fig. 9 that the deviation of the two methods is less than 2.7 ppm for ratio error and 2.9 μrad for phase displacement. The deviation between the results of the two methods is a systematic error. And it is worth noting that the error is mainly introduced from direct calibration of point at 10% and 20% of rated voltage with a 10 kV standard VT.

5.2. Experiment at 500/$\sqrt{3}$ kV

A 500/√3 kV VT_x with an accuracy class of 0.05 is chosen as the testing equipment. The measurement results of the three methods are compared.

Method #1: VT_3 (220/√3 kV) is used as a standard VT to calibrate VT_x at 20% and 40% rated voltage directly. The difference between these two points (△ε1) is the voltage coefficient of VT_x in the range of 20%～40% rated voltage (the corrected value when calibration results are taken to VT_3).

Method #2: the voltage coefficient of VT_x in the range of 20%～40% rated voltage is measured with the proposed method in this paper and the measurement result is △ε2.

Method #3: it is also measured with traditional method (Fig. 1). And measurement results for these three methods are shown in Table 4.

Table 4. Comparison between direct calibration and the proposed method at the reference points

	Method#1			***Method#2***	***Method #3***
	20%	40%	△ε1	△ε2	△ε3
***f* in ppm**	-33.2	-18.6	14.6	16.8	30.8
***δ* in μrad**	-42.1	-12.0	30.1	32.6	50.2

As *Method #1* is calibrated directly and takes the correct value of reference a VT to the final result, we could regard it for a moment as a reference. From Table 4 we can see that the deviation of traditional *Method #3* and new *Method #2* in this paper is 14.0 ppm and 17.6 μrad. The difference in phase displacement is mainly caused by capacitive leakage and adjacent interference.

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