

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

Hao Liu^{1,2)}, Lixue Chen¹⁾, Xue Wang²⁾, Teng Yao²⁾, Xiong Gu²⁾

- 1) State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, No. 1037 Luoyu Road Hongshan District, Wuhan, China (liuhao1@epri.sgcc.com.cn,  chenlixue@hust.edu.cn, +86 59 598 834)
 2) China Electric Power Research Institute, Wuhan, China (wangxue@epri.sgcc.com.cn, yaotengwuhan@163.com, nbbear1990@163.com)

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 $500/\sqrt{3}$ kV is 6.8 ppm for ratio error and 7 μ rad 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 $110/\sqrt{3}$ 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 μ rad for phase displacement.

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

© 2022 Polish Academy of Sciences. All rights reserved

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.

Copyright © 2022. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (CC BY-NC-ND 4.0 <https://creativecommons.org/licenses/by-nd/4.0/>), which permits use, distribution, and reproduction in any medium, provided that the article is properly cited, the use is non-commercial, and no modifications or adaptations are made.

Article history: received December 28, 2021; revised February 19, 2022; accepted March 9, 2022; available online April 27, 2022.

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 $400/\sqrt{3}$ 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 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 ,

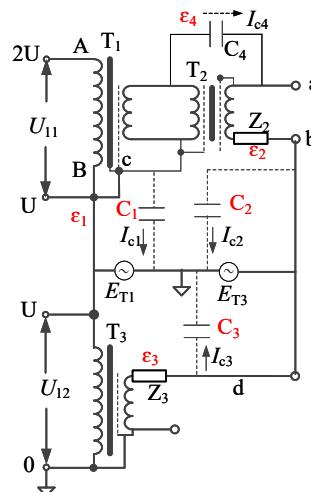


Fig. 1. Equivalent circuit of distributed capacitance.

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.

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 2a shows the principle of measuring the error of the upper-level VT T_1 and T_2 , written as ε_a , and. Figure 2b shows the error measurement for the lower-level VT T_3 , written as ε_b .

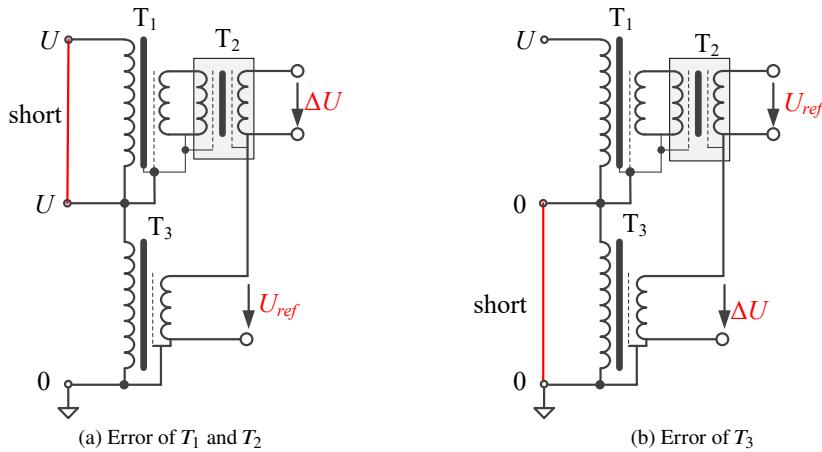


Fig. 2. Principle of the measurement.

Take Fig. 2a 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 $\Delta U = 0$. 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.

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.

	Applied voltage U_n (%)	15	30	60
ϵ_a	Ratio error in ppm	14.3	14.8	16.5
	Phase displacement in μrad	-10.2	-10.5	-12.2
ϵ_b	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:

$$[\dot{I}] = [Y] [\dot{U}], \quad (1)$$

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:

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

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.

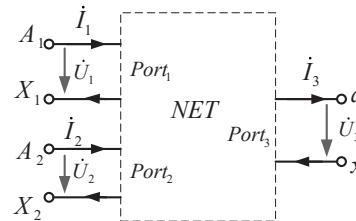


Fig. 3. Linear three-ports network.

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.

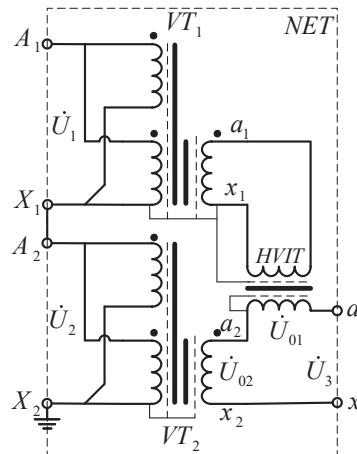
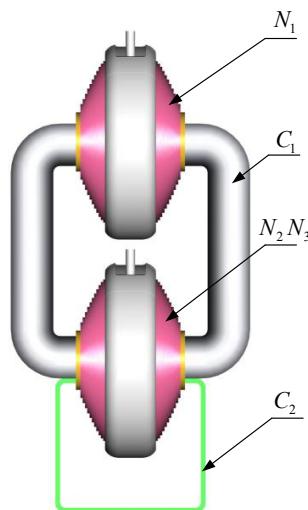


Fig. 4. Internal structure of the linear three-ports network.

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 110 kV 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:

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

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 VT₁ 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:

$$\dot{U}_{02} = n\dot{U}_2 + f\dot{U}_1, \quad (4)$$

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 VT₂, and $f\dot{U}_1$ is the disturbance voltage at the output port when VT₁ 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 VT₁ and HVIT are K and α , and the rated voltage ratio and ratio error of VT₂ are K and β , (3) and (4) can be further expressed as:

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

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

If the rated voltage ratio of the standard voltage transformer VT₃ 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 $(-\dot{U})$ is applied at $A_1 - X_1$, and voltage \dot{U} is applied simultaneously at $A_2 - X_2$ and VT₃. 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 ΔU in normal operation conditions), but not equal to zero. The input potential difference of the test set is $\Delta U(a-x)$. At this moment, the measured value of the test set is ε_1 ($\Delta U/U_{ref}$) and the ratio error of VT₃ is $\gamma(\dot{U})$. According to the definition of error of the transformer, the network output (\dot{U}_{31}) can be expressed as:

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

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

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

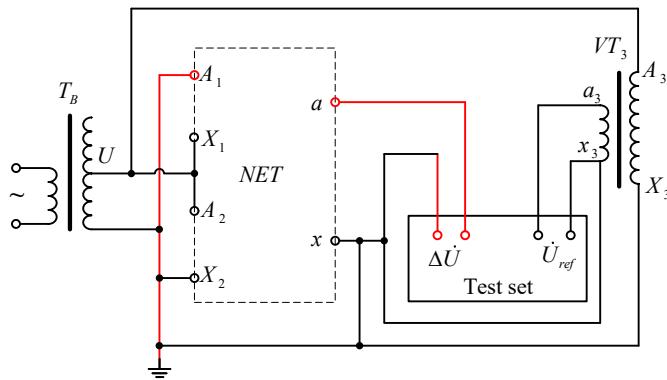


Fig. 6. Measurement of output response to the input port $A_2 - X_2$.

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 $\Delta U(a-a_3)$ 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:

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

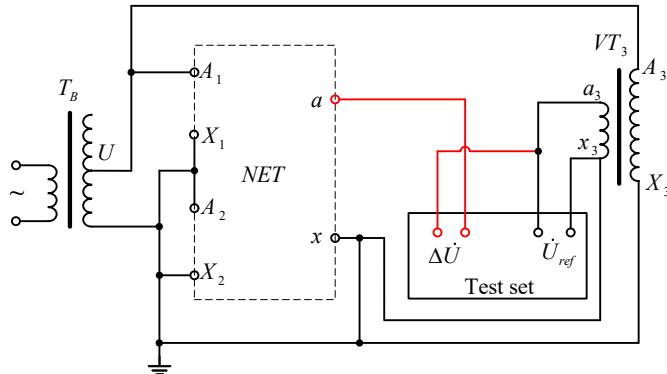


Fig. 7. Measurement of output response to the input port $A_1 - X_1$.

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

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

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 $\Delta U(a-a_3)$ 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:

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

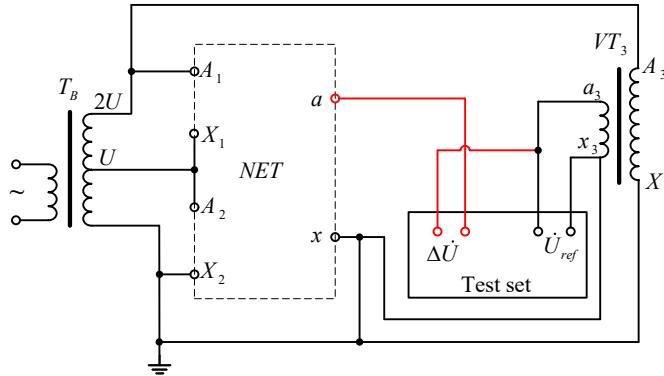


Fig. 8. Measurement of output responses to the input ports $A_1 - X_1$ and $A_2 - X_2$.

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

$$\dot{U}_{33} = \dot{U}_{01} + \dot{U}_{02} = \frac{\dot{U}}{K} (1 + \alpha) + (g + h + f)\dot{U} + \frac{\dot{U}}{K} (1 + \beta). \quad (12)$$

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

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

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

$$\dot{U}_{31} + 2\dot{U}_{32} = \dot{U}_{33}. \quad (14)$$

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

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

Finally, (15) can be deduced to:

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

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 $2^k U$ ($k = 1, 2, \dots$) could be determined.

4. Measurement uncertainty analysis

The measurement uncertainty of this series step-up method varies with different voltage levels. We take 500/kV as an example. 20% to 50% of rated voltage can be calibrated directly with a 220/ 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.

$$U_{f1} = \sqrt{\frac{1}{n} \sum_{i=1}^n u_{f1}^2} = 1 \times 10^{-6}, \quad (17)$$

$$U_{\delta 1} = \sqrt{\frac{1}{n} \sum_{i=1}^n u_{\delta 1}^2} = 1.2 \text{ } \mu\text{rad}. \quad (18)$$

2. A 220/ kV Standard VT. For a 500/ kV standard VT, the error under 20%~50% of rated voltage is calibrated with a 220/ 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/kV VT, we should use two 250/ kV in series with an accuracy class of 0.002. ε_m is 20 ppm and 20 μrad . 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 $0.01 \varepsilon_m$, 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 so an 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:

$$U_f = 2 \times \sqrt{\sum_{i=1}^5 u_i^2} = 6.8 \times 10^{-6} \quad (k = 2), \quad (19)$$

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

5. Experiment and results

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

A 110/ kV voltage transformer (VT₃) 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/ 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 VT₃ 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 VT₃ 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.

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

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.

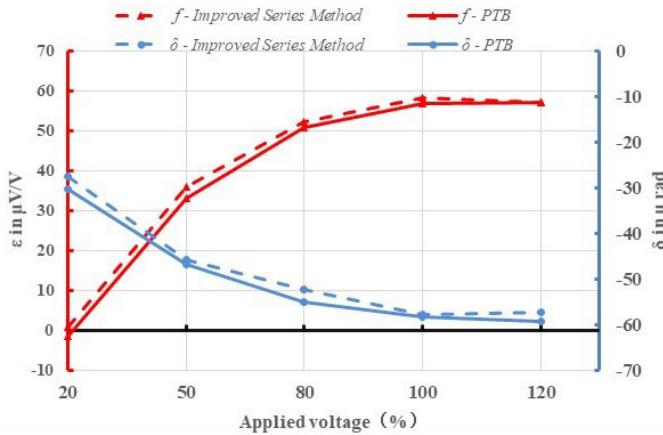


Fig. 9. Comparison of results with PTB.

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.

Table 3. Data of new series method.

(a) Ratio error

Applied voltage (%)	ε_1 in ppm	Applied voltage (%)	ε_2 in ppm	ε_3 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 (%)	ε_1 in μrad	Applied voltage (%)	ε_2 in μrad	ε_3 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

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

A $500/\sqrt{3}$ 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: VT₃ ($220/\sqrt{3}$ kV) is used as a standard VT to calibrate VT_x at 20% and 40% rated voltage directly. The difference between these two points ($\Delta\varepsilon 1$) is the voltage coefficient of VT_x in the range of 20%~40% rated voltage (the corrected value when calibration results are taken to VT₃).

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 $\Delta\varepsilon 2$.

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%	$\Delta\epsilon 1$	$\Delta\epsilon 2$	$\Delta\epsilon 3$
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 μ rad. The difference in phase displacement is mainly caused by capacitive leakage and adjacent interference.

References

- [1] Zhou, F., Mohns, E., Jiang, C., He, X., & Yue, C. (2014, August). 1000 V Self-calibrating Inductive Voltage Divider with coaxial-cable winding. In *29th Conference on Precision Electromagnetic Measurements (CPEM 2014)* (pp. 128–129). IEEE. <https://doi.org/10.1109/CPEM.2014.6898292>
- [2] Budovsky, I. F., Small, G. W., Gibbes, A. M., & Fiander, J. R. (2004, June). Calibration of 1000 V/50 Hz inductive voltage dividers and ratio transformers. In *2004 Conference on Precision Electromagnetic Measurements* (pp. 322–323). IEEE. <https://doi.org/10.1109/CPEM.2004.305595>
- [3] Hill, J. J., & Miller, A. P. (1962). A seven-decade adjustable-ratio inductively-coupled voltage divider with 0.1 part per million accuracy. *Proceedings of the IEE-Part B: Electronic and Communication Engineering*, 109(44), 157–162. <https://doi.org/10.1049/pi-b-2.1962.0180>
- [4] So, E., & Latzel, H. G. (2001). NRC-PTB intercomparison of voltage transformer calibration systems for high voltage at 60 Hz, 50 Hz, and 16.66 Hz. *IEEE Transactions on Instrumentation and Measurement*, 50(2), 419–421. <https://doi.org/10.1109/19.918156>
- [5] Borkowski, D., Nabielec, J., & Wetula, A. (2015, June). Experimental verification of the voltage divider with auto-calibration. In *2015 International School on Nonsinusoidal Currents and Compensation (ISNCC)* (pp. 1–5). IEEE. <https://doi.org/10.1109/ISNCC.2015.7174688>
- [6] Nabielec, J., & Wetula, A. (2016). A voltage divider with autocalibration—a version with single compensation. *Przegld Elektrotechniczny*, 92(11), 11–14. <https://doi.org/10.15199/48.2016.11.03>
- [7] Braun, A., Richter, H., & Danneberg, H. (1980). Determination of voltage transformer errors by means of a parallel-series step-up method. *IEEE Transactions on Instrumentation and Measurement*, 29(4), 490–492. <https://doi.org/10.1109/TIM.1980.4314987>
- [8] Leren, W. (1990, June). A series summation method for the determination of voltage ratios at power frequency with high accuracy. In *Conference on Precision Electromagnetic Measurements* (pp. 378–379). IEEE. <https://doi.org/10.1109/CPEM.1990.110068>
- [9] Leren, W. (1992). New circuit and application for voltage summation method in industrial frequency. *ACTA Metrologica Sinica*, 13(3), 221–225.
- [10] Li, Q., Wang, L., Zhang, S., Tang, Y., & Xu, Y. (2012). Method to determine the ratio error of DC high-voltage dividers. *IEEE Transactions on Instrumentation and Measurement*, 61(4), 1072–1078. <https://doi.org/10.1109/TIM.2011.2178672>

- [11] Zhou, F., Jiang, C., Lei, M., & Lin, F. (2019). Improved stepup method to determine the errors of voltage instrument transformer with high accuracy. *IEEE Transactions on Instrumentation and Measurement*, 69(4), 1308–1312. <https://doi.org/10.1109/TIM.2019.2909939>
- [12] Liu, H., Zhou, F., Chen, L., Lei, M., Yin, X., Jiang, C., & Liu, J. (2021). The Development of Precision $500/\sqrt{3}$ -kV Two-Stage Voltage Transformer With High-Voltage Excitation. *IEEE Transactions on Instrumentation and Measurement*, 70, 1–7. <https://doi.org/10.1109/TIM.2021.3053979>
- [13] Feng, Z., Chunyang, J., Min, L., Fuchang, L., & Shihai, Y. (2019). Development of ultrahigh-voltage standard voltage transformer based on series voltage transformer structure. *IET Science, Measurement & Technology*, 13(1), 103–107. <https://doi.org/10.1049/iet-smt.2018.5258>
- [14] Mohns, E., Chunyang, J., Badura, H., & Raether, P. (2018). A fundamental step-up method for standard voltage transformers based on an active capacitive high-voltage divider. *IEEE Transactions on Instrumentation and Measurement*, 68(6), 2121–2128. <https://doi.org/10.1109/TIM.2018.2880055>



Hao Liu received B.S. and M.S. degrees from North China Electric Power University, Beijing, China, in 2016. He is currently pursuing his Ph.D. degree in High voltage and insulation technology from the Huazhong University of Science and Technology (HUST), Wuhan, China. He joined the China Electric Power Research Institute in 2016. In 2019 he worked at the PTB as a guest scientist. His research interests include high-voltage insulation and high-voltage and heavy current measurement technology.



Teng Yao was born in 1990. She received M.S. degree from University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2016. She is currently engineer with the China Electric Power Research Institute. Her research interests include high-voltage and heavy current measurement technology.



Lixue Chen received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Huazhong University of Science and Technology (HUST), Wuhan, China, in 2005, 2007, and 2011, respectively. He is currently a Professor with the School of Electrical and Electronic Engineering, HUST. His current research interests include pulsed power technology and electromagnetic launching.



Xiong Gu was born in Hubei Province, China, in 1990. He received B.S. degrees from Si Chuan University, Chengdu, China, in 2012. He received M.S. degrees from Guang xi University, Nanning, China, in 2018. He joined China Electric Power Research Institute in 2018. His research interests include high-voltage insulation and high-voltage and heavy current measurement technology.



Xue Wang was born in 1987. She received the M.S. degrees in electrical engineering from the Huazhong University of Science and Technology (HUST), Wuhan, China, in 2014. She is currently engineer with the China Electric Power Research Institute. Her current research interests include high-voltage and heavy current measurement technology.