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Research of the State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV

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Abstract

All electrical energy is produced, transmitted and distributed at high voltages. In this case, the measurement of the amount of electricity is carried out by electricity meters together with voltage transformers (VTs). The largest capacities are transmitted and distributed on power transmission lines of voltage of class 750 kV. In Ukraine there are about two hundred measuring VTs of class 750 kV. In addition, power facilities have been actively built recently, which will also require the installation of 750 kV transformers.

Working VTs of substations for a class of 750 kV may have great weight and dimensions. Their height is 7 m and weight is 4000 kg. Working measurement standards have the same weight and dimensions. Therefore, obtaining the size of a physical quantity from the measurement standards of other countries is very difficult for two reasons: it is very difficult to transport such working measurement standards abroad; only a few countries have measuring instruments with a voltage of 750 kV.

The purpose of the article is to highlight the results of researches of the State Primary Standard of the unit of scaling factor of alternating current (AC) voltage up to 750/√3 kV, in particular: formation of the composition of a set of measuring instruments for the reproduction of the unit of scaling factor; establishing a method for reproducing the unit of scaling factor; estimation of uncertainty of measurements and other metrological characteristics while transferring the unit of scaling factor.

The article presents the results of the research of the newly established State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV, which are of great practical importance. Those researches are aimed at improving the metrological traceability of AC high-voltage at the national level.

Keywords: AC high-voltage; measurement standard; measurement; calibration; uncertainty of measurement.

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Introduction

All electrical energy is produced, transmitted and distributed at high voltages. In this case, the measurement of the amount of electricity is carried out by electricity meters together with voltage transformers (VTs). The largest capacities are transmitted and distributed on power transmission lines of voltage of class 750 kV. On the same power lines, electricity is transmitted abroad, including Western Europe. In Ukraine there are about two hundred measuring VTs of class 750 kV. In addition, power facilities (new units at Rivne and Khmelnytskyi nuclear power plants, Kyiv substation) have been actively built recently, which will also require the installation of 750 kV transformers.

The results of measurements with the help of VTs of class 750 kV are used in the accounting of electricity and safety control of working conditions. According to Article 20 of the Law of Ukraine "On Metrology and Metrological Activity", such measurements are subject to state metrological control. At the same time, in Ukraine there were no measurement standards for calibration of VTs of class 750 kV. In case of violation of the mentioned Law, such VTs were operated by non-certified, energy market participants were paid for electricity by non-certified VTs.

Working VTs of substations for a class of 750 kV may have great weight and dimensions. Their height is 7 m and weight is 4000 kg. Working measurement standards have the same weight and dimensions. Therefore, obtaining the size of a physical quantity from the measurement standards of other countries is very difficult for two reasons: it is very difficult to transport such working measurement standards abroad; only a few countries have measuring instruments with a voltage of 750 kV [1–5].

Researches of the new established State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV are of great practical importance and are aimed at improving the metrological traceability of alternating current (AC) high-voltage at the national level [6, 7].

Table 1

Metrological characteristics of the national measurement standards

Country	The largest value of the AC primary voltage range	Expanded relative uncertainty
Australia	550 kV	6.0×10^{-5}
Argentina	525 kV	3.0×10^{-5}
Spain	500 kV	1.0×10^{-4}
Ukraine	750/√3 kV	4.4×10^{-5}
Russian Federation	750/√3 kV	2.0×10^{-4}

The problem statement, aim and objectives of the study

The purpose of the article is to highlight the results of researches of the new established State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV, in particular:

- formation of the composition of a set of measuring instruments for the reproduction of the unit of scaling factor;
- establishing a method for reproducing the unit of scaling factor;
- estimation of uncertainty of measurements [8] and other metrological characteristics at transfer of the unit of scaling factor.

Bases of creation of the national standard

The Ukrainian State Program for the Development of the reference base for 2011–2015 provided for the creation of the State Primary Standard of unit of scaling factor of AC voltage up to 750/√3 kV. The main purpose of the scientific research was to ensure the uniformity and traceability of measurements in Ukraine for electrical quantities and to expand the range of measurements of AC voltage in Ukraine.

To implement the measurement standard, the method of current comparison was chosen, which involves the use of a high-voltage measuring capacitor and an AC bridge.

The advantages of measuring instrument which should receive the size of the unit of measurement from the State Primary Standard are the following: electricity (accounting for energy resources and protection systems for personnel and equipment); instrument making (production of high-voltage measuring and testing equipment); scientific research (measurement of the scaling factor of AC voltage during physical experiments), etc.

The created State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV in 2018 was registered in the register of the national measurement standards – NDETU EM-01-2019. Metrological characteristics of the created Standard are at the level of characteristics of installations of similar purpose of such technically developed countries as Australia, Argentina, Spain and the Russian Federation (Table 1) [9].

The availability of the state primary measurement standard created a system of metrological support for this subtype of measurements independent from the national measurement standards of other states.

The composition of the national measurement standard

The State Primary Standard of the unit of scaling factor AC voltage up to 750/√3 kV is designed to reproduce, store and transfer the unit of scaling factor of AC voltage to secondary measurement standards, working measurement standards in the range of primary AC voltage from minus 750/√3 kV to 750/√3 kV. A general view of the State Primary Standard is presented in Fig. 1.

The measurement standard consists of a set of precision measuring instruments: high-voltage reference capacitor MSR-600; measuring capacitor SA 6003; high-voltage reference bridge MVE-01 (hereinafter – AC bridge); AC voltage source DZC-520-1; load box SA 5055.

The measurement standard is keeping in the State Enterprise "Ukrmetrteststandard" (Kyiv, Ukraine) and the laboratory of high voltage technology Igor Sikorsky National University "Kyiv Polytechnic Institute". The area of the room where the standard is located is 40 m². The standard is used to calibrate VTs used in relay protection systems for personnel and equipment in electrical installations.

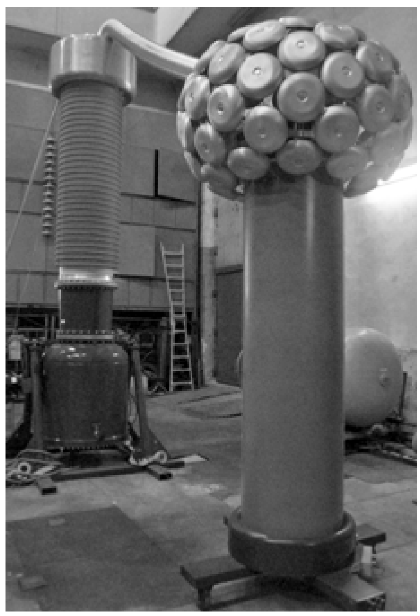

Fig. 1. The general view of the State Primary Standard of the unit of scaling factor of AC voltage up to 750/√3 kV

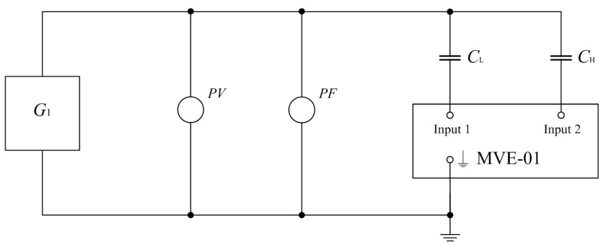

Fig. 2. The scheme for measurements on the first stage

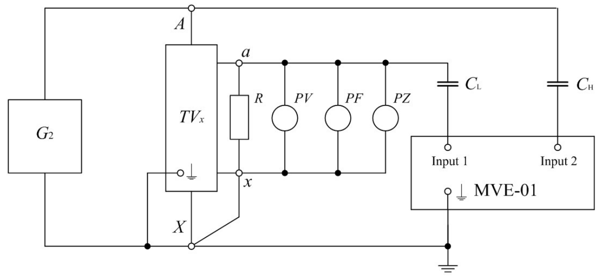

Fig. 3. The scheme for measurements on the second stage

The results of research of the measurement standard

The method of comparing currents using an AC bridge and two measuring capacitors is used to reproduce and store the unit of scaling factor of AC voltage. Measurements during the reproduction of the unit of scaling factor of AC voltage are performed in two stages: for first stage using the scheme according to Fig. 2 and for second stage using the scheme according to Fig. 3.

In Fig. 2 and Fig. 3 the following abbreviations introduced: G_1 is voltage source up to 1000 V; G_2 is high-voltage source; *PV* is voltmeter; *PF* is frequency meter; *PZ* is non-linear distortion meter; *R* is load box; TV_x is calibrated VT; C_L is low-voltage measuring capacitor; C_H is high-voltage measuring capacitor; MVE-01 is an AC bridge.

To determine the value of the deviation of the scaling factor of AC voltage, the ratios of the currents through the capacitors in the first and second stages (K_1 and K_2 accordingly) are used by the formulas:

$$K_1 = \frac{C_L\sqrt{1+\mathrm{tg}^2\delta_{C_L}}}{C_{V1}\sqrt{1+\mathrm{tg}^2\delta_{C_{H1}}}}, \quad (1)$$

$$K_2 = \frac{C_L\sqrt{1+\mathrm{tg}^2\delta_{C_L}}}{C_{H2}\sqrt{1+\mathrm{tg}^2\delta_{C_{H2}}}}, \quad (2)$$

where $\mathrm{tg}\,\delta_{C_{H1}}$ and $\mathrm{tg}\,\delta_{C_{H2}}$ are tangent of the dielectric loss angle of high-voltage capacitor C_H for first and second stages accordingly.

The value of the deviation of the scaling factor of AC voltage of the VT ε_U determined by the formula, as a percentage:

$$\varepsilon_U = \left(1 - \frac{K_1}{K_2 \cdot K_{\mathrm{nom}}}\right)100\%. \quad (3)$$

The absolute difference between the phases of the primary and secondary voltage of VT δ_U determined by the formula, in minutes:

$$\delta_U = \mathrm{arctg}\,\delta_{C_{H1}} - \mathrm{arctg}\,\delta_{C_{H2}}. \quad (4)$$

The scaling factor of AC voltage of the VT is determined by the formula:

$$K_{VT} = \frac{K_{\mathrm{nom}}}{1+\varepsilon_U/100}. \quad (5)$$

The standard deviation for measuring the deviation of the scaling factor of AC voltage ε_U is determined by the formula:

$$S_{\varepsilon_U} = \sqrt{\begin{aligned}&\left(\frac{\partial\varepsilon_U}{\partial(C_L/C_{H1})}\right)^2 S^2_{\frac{C_L}{C_{H1}}} + \left(\frac{\partial\varepsilon_U}{\partial(C_L/C_{H2})}\right)^2 S^2_{\frac{C_L}{C_{H2}}} + \\ &+ \left(\frac{\partial\varepsilon_U}{\partial(\mathrm{tg}\,\delta_{C_{H1}})}\right)^2 S^2_{\mathrm{tg}\,\delta_{C_{H1}}} + \left(\frac{\partial\varepsilon_U}{\partial(\mathrm{tg}\,\delta_{C_{H2}})}\right)^2 S^2_{\mathrm{tg}\,\delta_{C_{H2}}}\end{aligned}}, \quad (6)$$

where $S_{\frac{C_L}{C_{H1}}}$ and $S_{\frac{C_L}{C_{H2}}}$ are standard deviations for measurement of the ratio C_L/C_{H1} and C_L/C_{H2} accordingly; $S_{\mathrm{tg}\,\delta_{C_{H1}}}$ and $S_{\mathrm{tg}\,\delta_{C_{H2}}}$ are standard deviations for measurement of the tangents of the dielectric loss angle $\mathrm{tg}\,\delta_{C_{H1}}$ and $\mathrm{tg}\,\delta_{C_{H2}}$ accordingly.

The standard deviation for measurement of the absolute phase difference between the primary and secondary voltages S_{δ_U} is calculated by the formula:

$$S_{\delta_U} = \sqrt{S^2_{\delta_{C_{H1}}} + S^2_{\delta_{C_{H2}}}}, \quad (7)$$

where $S_{\delta_{C_{H1}}}$ and $S_{\delta_{C_{H2}}}$ are standard deviation for measurement of the tangent of the angle of dielectric loss $\mathrm{tg}\,\delta_{C_{H1}}$ and $\mathrm{tg}\,\delta_{C_{H2}}$ accordingly, determined by the formulas:

$$S_{\delta_{C_{H1}}} = \mathrm{arctg}\left(S_{\mathrm{tg}\,\delta_{C_{H1}}}\right),\; S_{\delta_{C_{H2}}} = \mathrm{arctg}\left(S_{\mathrm{tg}\,\delta_{C_{H2}}}\right). \quad (8)$$

The limits of non-excluded systematic error for measurement of the deviation of the scaling factor of AC voltage ε_U is determined by the formula:

$$\Theta_{\varepsilon_U} = 1.4\sqrt{\begin{aligned}&\left(\frac{\partial\varepsilon_U}{\partial(C_L/C_{H1})}\right)^2 \Theta^2_{\frac{C_L}{C_{H1}}} + \left(\frac{\partial\varepsilon_U}{\partial(C_L/C_{H2})}\right)^2 \Theta^2_{\frac{C_L}{C_{H2}}} + \left(\frac{\partial\varepsilon_U}{\partial(C_L/C_{H2})}\right)^2 \Theta^2_{CB} + \\ &+ \left(\frac{\partial\varepsilon_U}{\partial(\mathrm{tg}\,\delta_{C_{H1}})}\right)^2 \Theta^2_{\mathrm{tg}\,\delta_{C_{H1}}} + \left(\frac{\partial\varepsilon_U}{\partial(\mathrm{tg}\,\delta_{C_{H2}})}\right)^2 \Theta^2_{\mathrm{tg}\,\delta_{C_{H2}}} + \left(\frac{\partial\varepsilon_U}{\partial(\mathrm{tg}\,\delta_{C_{H2}})}\right)^2 \Theta^2_{\mathrm{tg}\,\delta_{C_H}}\end{aligned}}, \quad (9)$$

where $\Theta_{\frac{C_L}{C_{H1}}}$ and $\Theta_{\frac{C_L}{C_{H2}}}$ are non-excluded systematic errors for measurement of the ratio C_L/C_{H1} and C_L/C_{H2} accordingly;
Θ_{C_H} is non-excluded systematic error due to the dependence of the capacitance of the high-voltage reference capacitor MSR-600 on the voltage;
$\Theta_{\text{tg}\,\delta_{C_{H1}}}$ and $\Theta_{\text{tg}\,\delta_{C_{H2}}}$ are non-excluded systematic errors for measurement of the tangent of the dielectric loss angle $\text{tg}\,\delta_{C_{H1}}$ and $\text{tg}\,\delta_{C_{H2}}$ accordingly;
$\Theta_{\text{tg}\,\delta_{C_H}}$ is non-excluded systematic error for measurement of the tangent of the dielectric loss angle of high-voltage reference capacitor MSR-600.

The limits of the non-excluded systematic error for measurement of the absolute phase difference between the primary and secondary voltages are calculated by the formula:

$$\Theta_{\delta_U} = \pm\left(\left|\Theta_{\delta_{C_{H1}}}\right| + \left|\Theta_{\delta_{C_{H2}}}\right| + \left|\Theta_{\delta_{C_H}}\right|\right), \quad (10)$$

where $\Theta_{\delta_{C_{H1}}}$ and $\Theta_{\delta_{C_{H2}}}$ are non-excluded systematic errors for measurement of the tangent of the dielectric loss angle $\text{tg}\,\delta_{C_{H1}}$ and $\text{tg}\,\delta_{C_{H2}}$ accordingly;
$\Theta_{\delta_{C_H}}$ is non-excluded systematic error due to the tangent of the dielectric loss angle of the high-voltage reference capacitor MSR-600.

The limits of non-excluded systematic error for measurement of the deviation of the scaling factor of AC voltage ε_U and for measurement of the absolute difference between the primary and secondary voltages δ_U are determined for the values of scaling factor of the AC voltage $\frac{330/\sqrt{3}\,\text{kV}}{100\ \text{V}}$ and $\frac{750/\sqrt{3}\,\text{kV}}{100/3\ \text{V}}$, the values of the absolute phase difference of primary and secondary voltages 0' and 10'.

The standard deviation S_{ε_U} and the limits of non-excluded systematic error Θ_{ε_U} in measuring the scaling factor of AC voltage and the standard deviation S_{δ_U} and the limits of non-excluded systematic error in measuring the absolute phase difference of primary and secondary voltages Θ_{δ_U} are shown in Table 2.

The combined standard uncertainty for reproduction of the scaling factor of AC voltage is determined by the formula:

$$U_{\varepsilon_U} = \sqrt{S_{\varepsilon_U}^2 + \Theta_{\varepsilon_U}^2/3}. \quad (11)$$

The combined standard uncertainty for measurement of the absolute phase difference between the primary and secondary voltages is determined by the formula:

$$U_{\delta_U} = \sqrt{S_{\delta_U}^2 + \Theta_{\delta_U}^2/3}. \quad (12)$$

The combined standard uncertainties U_{ε_U} and U_{δ_U} in the reproduction of the scaling factor of AC voltage are shown in Table 3.

Table 2

The standard deviations and the limits of non-excluded systematic errors

K_{nom}	$\frac{330/\sqrt{3}\ \text{kV}}{100\ \text{V}}$		$\frac{750/\sqrt{3}\ \text{kV}}{100/3\,\text{V}}$	
	0'	10'	0'	10'
S_{ε_U}	8.0909×10^{-7}	8.0915×10^{-7}	8.0909×10^{-7}	8.0915×10^{-7}
S_{δ_U}	0.01135	0.01135	0.01135	0.01135
Θ_{ε_U}	2.395×10^{-5}	5.796×10^{-5}	4.362×10^{-5}	7.632×10^{-5}
Θ_{δ_U}	0.103	0.153	0.103	0.153

Table 3

The combined standard uncertainties in the reproduction of the scaling factor of AC voltage

K_{nom}	$\frac{330/\sqrt{3}\ \text{kV}}{100\ \text{V}}$		$\frac{750/\sqrt{3}\ \text{kV}}{100/3\,\text{V}}$	
	0'	10'	0'	10'
U_{ε_U}	1.3851×10^{-5}	3.3473×10^{-5}	2.5197×10^{-5}	4.4071×10^{-5}
U_{δ_U}	0.0605	0.0891	0.0605	0.0891

Summary

The creation of the primary measurement standard of the unit of scaling factor of AC voltage in the range of up to 750 kV made it possible to solve the issue of ensuring metrological traceability of the corresponding working measurement standards at the national level. Metrological characteristics of the created primary measurement standard are at the level of characteristics of installations of similar purpose of such technically developed countries as Australia, Argentina, Spain and the Russian Federation.

Дослідження державного первинного еталона одиниці коефіцієнта масштабного перетворення напруги змінного струму до 750/√3 кВ

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Анотація

Уся електрична енергія виробляється, передається й розподіляється при високій напрузі. У цьому випадку вимірювання кількості електроенергії здійснюється лічильниками електроенергії разом із трансформаторами напруги (ТН). Найбільші потужності передаються й розподіляються на лініях електропередач класом напруги 750 кВ. В Україні існує близько двохсот вимірювальних ТН класу 750 кВ. Крім того, останнім часом активно будуються енергетичні об'єкти, що також потребуватиме встановлення ТН класу 750 кВ.

Робочі ТН підстанцій класу 750 кВ можуть мати велику вагу та габарити. Звичайно їх висота становить 7 м, а вага – 4000 кг. Робочі еталони мають таку ж вагу і розміри. Тому отримати розмір фізичної величини за еталонами інших країн практично неможливо з двох основних причин: дуже складно транспортувати такі робочі еталони за кордон; лише деякі країни мають первинні еталони для напруги 750 кВ.

Метою статті є висвітлення результатів досліджень державного первинного еталона одиниці коефіцієнта масштабного перетворення змінної напруги до 750/√3 кВ, зокрема: формування складу еталонних вимірювальних приладів для відтворення одиниці коефіцієнта масштабного перетворення; встановлення способу відтворення одиниці коефіцієнта масштабного перетворення; оцінка невизначеності вимірювань та інших метрологічних характеристик при передаванні одиниці коефіцієнта масштабного перетворення.

Наведено результати дослідження новоствореного державного первинного еталона одиниці коефіцієнта масштабного перетворення змінної напруги до 750/√3 кВ, які мають велике практичне значення. Ці дослідження спрямовані на поліпшення метрологічної простежуваності високовольтних змінних струмів на національному рівні.

Ключові слова: змінний струм високої напруги; еталон; вимірювання; калібрування; невизначеність вимірювання.

Исследование государственного первичного эталона единицы коэффициента масштабного преобразования переменного напряжения до 750/√3 кВ

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Аннотация

Вся электрическая энергия производится, передается и распределяется на высоком напряжении. В этом случае измерение количества электроэнергии производится электросчетчиками совместно с трансформаторами напряжения (ТН). Наибольшие мощности передаются и распределяются по линиям электропередач класса напряжения 750 кВ.

В Украине насчитывается около двухсот измерительных ТН класса 750 кВ. Кроме того, в последнее время активно строятся энергообъекты, что также потребует установки ТН на 750 кВ.

Рабочие ТН подстанций класса 750 кВ могут иметь большой вес и габариты. Обычно их высота составляет 7 м, а вес – 4000 кг. Рабочие эталоны имеют аналогичный вес и габариты. Следовательно, получение размера физической величины от эталонов других стран практически невозможно по двум основным причинам: очень трудно транспортировать такие рабочие эталоны за границу; только несколько стран имеют первичные эталоны с напряжением 750 кВ.

Представлены результаты исследований вновь созданного государственного первичного эталона единицы коэффициента масштабного преобразования переменного напряжения до 750/√3 кВ, имеющие большое практическое значение. Эти исследования направлены на улучшение метрологической прослеживаемости переменного тока высокого напряжения на национальном уровне.

Ключевые слова: переменный ток высокого напряжения; эталон; измерение; калибровка; неопределенность измерения.

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