ASSESSING TRANSFORMATION RATIO OF VOLTAGE TRANSFORMER UNDER NON-SINUSOIDAL SUPPLY VOLTAGE CONDITIONS

Yusifbayli Nurali Adil[1], Guliyev Huseyngulu Bayram[2*],
Hajiyev Naib Ismihan[3], Huseynov Nijat Ramiz[4]

•

[1, 2*,3]Azerbaijan Technical University, Baku, Azerbaijan AZ1073, H. Javid avenue 25
[4]Sumgait State University, Sumgait, Azerbaijan AZ5008, Baku Street 1
[1]Emails: nyusifbeyli@area.gov.az, Orcid: 0000-0001-7948-4682
[2*]Emails: huseyngulu@mail.ru, Orcid: 0009-0006-7362-0619
[3]Emails: naib.haciyev.sdu@mail.ru
[4]Emails: nijat.huseyn.98@gmail.com

Abstract

Voltage transformers are rarely subjected to periodic inspection and testing while in operation, which is the reason for the difference between actual transformation ratios and their rated values. The frequency characteristics of voltage transformers are checked neither. Therefore, there can be large errors in the case of non-sinusoidal supply voltage. Existing studies on the study of voltage transformer faults reflect the results of the study of the equivalent circuit based on traditional lumped-parameter circuits. However, it should be noted that for high-frequency circuits and at the same time from the point of view of taking into account the structure of the windings, increasing the accuracy of the research results is an urgent issue. The case of non-sinusoidal supply voltage is of great scientific interest in this regard. Therefore, considering the voltage transformer as a distributed-parameter circuit, its fault under non-sinusoidal supply voltage was investigated and studied. This work explores errors of voltage transformers in the presence of non-sinusoidal voltage. To this end, a mathematical model of the transformation ratio is built considering the equivalent circuit of transformer as a distributed-parameter circuit.

Keywords: power quality, voltage transformer, lumped-parameter circuit, distributed- parameter circuit, non-sinusoidal voltage, transformation ratio

I. Introduction

One of the main requirements, which are imposed in power supply systems of industrial enterprises on results of experimental studies on metering electricity and monitoring its quality is the reliability of the results, i.e. correspondence of calculated and measured parameters to their real values. The reliability of calculation and measurement results depends both on the error of calculation methods (methodological error) and the error of information and measuring tools (measurement error). These issues are crucial when metering electricity to assess the distortion of the current and voltage curves [1-5]. GOST (State Standard) 3341-2013 establishes permissible error standards for measurements of power quality indicators. This standard is ±10% for the total harmonic distortion and ±5% - for the harmonic factor of the n-th harmonic components [4–7].

The reliability of calculations of non-sinusoidality indicators based on instantaneous voltage (current) values and measurement results can be objectively assessed by comparing these indicators with their real values. In actuality, however, there is unknown information about amplitudes and phase shifts of individual harmonic voltage (current) components. At the same time, all instruments and computer systems for measuring power quality indicators are separated from the high-voltage network through voltage and current measuring transformers. The main difficulty encountered is that the voltage and current measuring transformers operating in substations are sources of measurement error themselves [8-12]. These errors are mainly due to the following factors:

- A transformer accuracy class;
- A mismatch between transformation ratio and its nominal value;
- A lack of information about transformation ratio for high harmonics.

The first two above-listed factors can be eliminated by initial testing and, if necessary, by replacing instrument transformers, whereas the third factor requires additional special research. High harmonic voltage (current) distorts the transformation ratios of measuring transformers, which also increases measurement errors. It must be borne in mind that inductive voltage transformers may experience resonance phenomena at frequencies above 1 kHz (harmonic 20 and higher), which is also an additional source of error [13-16].

Voltage transformers (VT) are rarely inspected and tested during operation, which leads to the discrepancy between real transformation ratios and their nominal values [17], [18-20]. In addition, it is also important to know the frequency characteristics of VT to assess the impact of the harmonic factors of the n-th harmonic components and the total harmonic distortion on VT transformation ratio. These VT characteristics have not been fully investigated. Therefore, the VT errors may exceed their permissible values not only for high but also for the fundamental harmonic voltage (current). As a result, the readings of measuring and metering instruments can be significantly distorted.

In the context of the above assumptions, the study on the VT frequency characteristics with a focus on the distortion of the supply voltage curve is a pressing issue.

II. Mathematical model of the transformation ratio for a VT lumped-parameter circuit

Some works address the assessment of the errors of instrument transformers in the electricity metering system [13], [16]. The error of the VT transformation ratio under a non-sinusoidal voltage is examined in [3], [4]. The VT equivalent circuit is considered as a lumped-parameter circuit. The following formula is obtained for the transformation ratio of the n-th harmonic (Figure 1):

$$K'_{t,n} = 1 + \frac{Z_{1n}}{Z_{mn}} + \frac{Z_{1n} Z'_{2n}}{Z_{mn} Z_{mn}} + \frac{Z_{1n} + Z'_{2n}}{Z'_{Hn}}, \tag{1}$$

where, $Z_{1n}; Z_{mn}$ are the complex impedance of the primary winding and magnetization for the n-th harmonic, respectively; Z_{2n} is the complex impedance of the secondary winding connected to the primary winding; Z'_{Hn} is the complex load impedance for the n-th harmonic ($n = \overline{2, 40}$).

The study of VT transformation ratio considering voltage harmonic components based on the

VT lumped-parameter circuit indicates that in this case, large VT errors arise and it is impossible to use formulas (1) above the 13th harmonic. As a result, the information delivered when measuring distortion indicators and metering electricity in high-voltage circuits is incorrect.

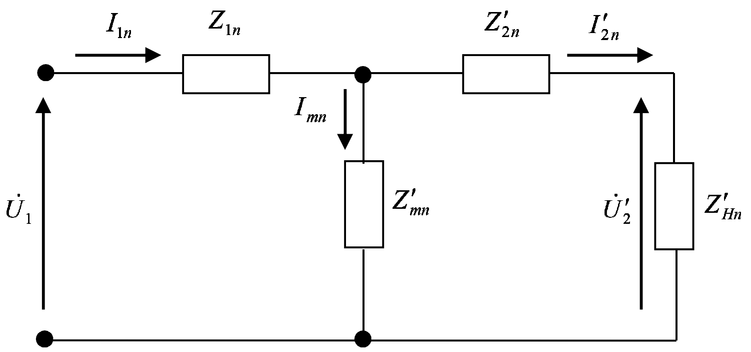

Figure 1: *Equivalent circuit of VT with lumped parameters*

III. Mathematical model of the transformation ratio for a VT distributed-parameter circuit.

To accurately determine the VT transformation ratio for high harmonics when dealing with a non-sinusoidal supply voltage, it is crucial to consider high voltage and high frequency circuits as distributed-parameter circuits. This means modeling VT under high frequencies and voltages as a transmission line with distributed parameters. This aspect of voltage transformers was not studied or was studied insufficiently. Therefore, comprehensive studies of VTs are required for high harmonic voltage with VT modeled as an element with distributed parameters.

The VT distributed-parameter circuit is shown in Figure 2.

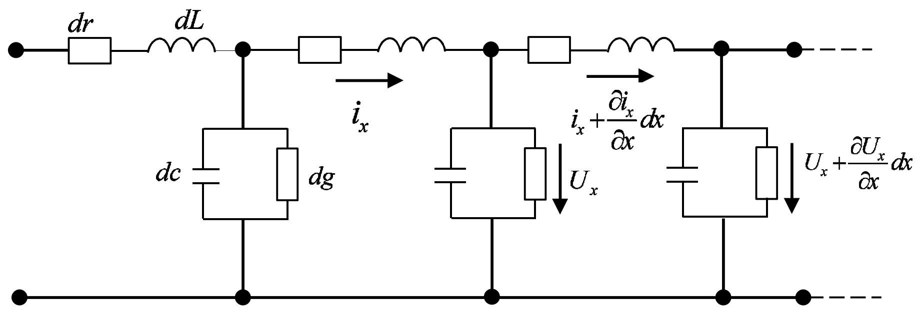

Figure 2: *The VT distributed-parameter circuit.*

As is known from the theory of electrical engineering, high-voltage and high-frequency circuits must factor in the wave nature of power transmission. In this case, to analyze the power transmission process, a line with length l is represented as a distributed-parameter circuit, where each element with an infinitesimal length dx has active resistance $r_0$dx, inductive reactance $x_0$dx, conductance $g_0$dx, and capacitance c_0dx, i.e., all parameters in the diagram in Fig. 1 are reduced to sections of infinitesimal length dx. Therefore, we can write the following equalities:

$$\left.\begin{aligned} dr &= r_0 dx \\ dL &= L_0 dx \\ dc &= c_0 dx \\ dg &= g_0 dx \end{aligned}\right\} \tag{2}$$

where r_0 is the linear active resistance of the line; L_0 is circuit inductance; c_0 capacitance between turns of windings; g_0 is conductance between the turns.

We assume that the VT parameters (active resistance and inductance, capacitance and conductance) are distributed evenly along the line.

In the long lines, at a frequency of 50 Hz, active and reactive currents do not remain constant. This, in turn, causes the voltage to change along the line. Therefore, by writing differential equations expressing the electrical state of a line with distributed parameters, in which voltage with a non-sinusoidal law of change is applied to the terminals, and solving these equations, one can determine the patterns of voltage and current distribution along the line.

Based on Figure 1, we can write the corresponding equations. To do this, the balance equations are written down for each element dx

$$\left.\begin{aligned} i_x &= i_x + \frac{\partial i_x}{\partial x}dx + u_x dg + dc\frac{\partial x}{\partial t} \\ u_x &= u_x + \frac{\partial u_x}{\partial x}dx + \left(i_x + \frac{\partial i_x}{\partial x}dx\right)dr + dL\frac{\partial}{\partial t}\left(i_x + \frac{\partial i_x}{\partial x}dx\right) \end{aligned}\right\} \tag{3}$$

This equation can be written as follows

$$\frac{\partial i_x}{\partial x}dx + u_x dg + dc\frac{\partial u_x}{\partial t} = 0$$

Let us divide both sides of the equation by dx. Then we have

$$\frac{\partial i_x}{\partial x} + u_x\frac{dg}{dx} + \frac{dc}{dx}\cdot\frac{\partial u_x}{\partial t} = 0\ .$$

From here we arrive at

$$\frac{\partial i_x}{\partial x} + g_0 u_x + c_0\frac{\partial u_x}{\partial t} = 0 \tag{4}$$

Accordingly, the following can be written for the second equation of system (3)

$$\frac{\partial u_x}{\partial x} + i_x\frac{\partial r}{\partial x} + \frac{\partial i_x}{\partial x}dr + \frac{\partial i_x}{\partial t}\cdot\frac{dL}{dx} + dL\frac{\partial i_x}{\partial x} = 0$$
$$\frac{\partial u_x}{\partial x} + r_0 i_x + \partial i_x r_0 + L_0\frac{\partial i_x}{\partial t} + dL\frac{\partial i_x}{\partial x} = 0$$

Here, given that $\partial i_x r_0 \approx 0,\ dL\frac{\partial i_x}{\partial x} \approx 0$, we obtain

$$\frac{\partial u_x}{\partial x} + r_0 i_x + L_0\frac{\partial i_x}{\partial t} = 0 \tag{5}$$

Thus, we have the following systems of partial differential equations:

$$\left.\begin{aligned}\frac{\partial u_x}{\partial x}+r_0 i_x+L_0\frac{\partial i_x}{\partial t}=0\\ \frac{\partial i_x}{\partial x}+g_0 u_x+c_0\frac{\partial u_x}{\partial t}=0\end{aligned}\right\} \tag{6}$$

In the case of non-sinusoidal voltage $\underline{U}$ and current $\underline{I}$, they can be expanded into a Fourier series

$$\left.\begin{aligned}\underline{u}=\sum_{n=1}^{\infty}U_{n,m}\exp(jnmt)\\ \underline{i}=\sum_{n=1}^{\infty}I_{n,m}\exp(jnmt)\end{aligned}\right\} \tag{7}$$

where $U_{n,m}=f_1(x)$ and $I_{n,m}=f_2(x)$. Let us obtain partial derivatives from equations (7)

$$\left.\begin{aligned}\frac{\partial u_x}{\partial x}=\sum_{n=1}^{\infty}\frac{dU_{n,m}}{dx}\exp(jnmt)\\ \frac{\partial i_x}{\partial x}=\sum_{n=1}^{\infty}\frac{dI_{n,m}}{dx}\exp(jnmt)\end{aligned}\right\} \tag{8}$$

Substituting equations (7) and (8) into (6), we obtain

$$\left.\begin{aligned}\sum_{n=1}^{\infty}\left[\frac{dU_{n,m}}{dx}+r_0 I_{n,m}+L_0 I_{n,m}jnm\right]\cdot\exp(jnmt)=0\\ \sum_{n=1}^{\infty}\left[\frac{dI_{n,m}}{dx}+g_0 U_{n,m}+c_0 U_{n,m}jnm\right]\cdot\exp(jnmt)=0\end{aligned}\right\}$$

It is known that $\exp(jnmt)\neq 0$. The sign of the sum is not considered. In this case, for the n-th harmonic voltage and current, the following expressions can be written:

$$\left.\begin{aligned}\frac{d\underline{U}_{n,m}}{dx}=r_0\underline{I}_{n,m}+jnmL_0\underline{I}_{n,m}=0\\ \frac{d\underline{I}_{n,m}}{dx}=g_0\underline{U}_{n,m}+jnmc_0\underline{U}_{n,m}=0\end{aligned}\right\}$$

From here, we obtain:

$$\left.\begin{aligned}-\frac{dU_{n,m}}{dx}=(r_0+jn\omega L_0)I_{n,m}\\ -\frac{dI_{n,m}}{dx}=(g_0+jn\omega c_0)U_{n,m}\end{aligned}\right\} \tag{9}$$

Considering that $r_0+jn\omega L_0=Z_0$ and $g_0+jn\omega c_0=Y_0$, we have the following systems of equations:

$$\left.\begin{aligned}-\frac{dU_{n,m}}{dx}=Z_0 I_{n,m}\\ -\frac{dI_{n,m}}{dx}=Y_0 U_{n,m}\end{aligned}\right\} \tag{10}$$

Equation (10) is a telegraph equation obtained for the n-th harmonic voltage and current according to a VT distributed-parameter circuit and an applied non-sinusoidal supply voltage. We solve equation (10). To do this, we obtain the derivative of the first equation and take it into account in the second equation. Then we write

$$-\frac{d^2\underline{U}_{n,m}}{dx^2}=Z_0\frac{d\underline{I}_{n,m}}{dx} \tag{11}$$

or

$$-\frac{d^2\underline{U}_{n,m}}{dx^2}=Z_0Y_0\underline{U}_{n,m}=0 \tag{12}$$

Denoting $d/dx=P$, we obtain the characteristic equation

$$P^2-Z_0Y_0=0 \tag{13}$$

From equation (12), we obtain the following expression

$$P=\pm\sqrt{Z_0Y_0}=\pm P_0$$

As is known, solution to (12) will be in the form

$$\underline{U}_{n,m}=A_{1,n}\exp(P_0x)+A_{2,n}\exp(-P_0x), \tag{14}$$

where P_0 is the solution to equation (13); $A_{1,n}$, $A_{2,n}$ are still unknown coefficients. These unknown coefficients are determined from the initial conditions. For x=0, we have

$$U\big|_{x=0}=U_{n,m,0} \text{ and } A_{1,n}+A_{2,n}=U_{n,m,0} \tag{15}$$

The second condition is written based on the first equation of system (10) for the case $x=l$. Then we have

$$\left.\frac{d\underline{U}_{n,m}}{dx}\right|_{x=l}=-Z_0\underline{I}_{n,m}\big|_{x=l}$$

In the case of an open circuit at the end of the transformer, we have $i_2=0$, and since the VT operates in close-to–no-load conditions, we obtain:

$$\left.\frac{d\underline{U}_{n,m}}{dx}\right|_{x=l}=0 \tag{16}$$

Calculating the derivative from equation (14) and substituting it into (16) we have:

$$\left.\frac{d\underline{U}_{n,m}}{dx}\right|_{x=l}=P_0\left(A_{1,n}\exp(P_0l)-A_{2,n}\exp(-P_0l)\right)=0$$

Or

$$A_{1,n}\exp(P_0l)-A_{2,n}\exp(-P_0l)=0\Rightarrow A_{2,n}=A_{1,n}\exp(2P_0l) \tag{17}$$

Substituting (17) into (15), we get:

$$A_{1,n} + A_{1,n}\exp(2P_0 l) = U_{n,m,0}$$

$$A_{1,n} = \frac{U_{n,m,0}}{1+\exp(2P_0 l)} \tag{18)}$$

and

$$A_{2,n} = \frac{U_{n,m,0}\exp(2P_0 l)}{1+\exp(2P_0 l)} = \frac{U_{n,m,0}}{1+\exp(-2P_0 l)} \tag{19}$$

Given the obtained expressions for the integral constants $A_{1,n}$ and $A_{2,n}$ in (14), we have:

$$\underline{U}_{n,m} = U_{n,m,0}\left(\frac{\exp(P_0 x)}{1+\exp(2P_0 l)} + \frac{\exp(-P_0 x)}{1+\exp(-2P_0 l)}\right)$$

At the end of the line, voltage at $x = l$ will be $U_{n,m}\big|_{x=l} = U_{n,m,l}$. Then we have:

$$\begin{aligned} U_{n,m,l} &= U_{n,m,0}\left(\frac{1}{\exp(P_0 l)+\exp(-P_0 l)} + \frac{1}{\exp(P_0 l)+\exp(-P_0 l)}\right) = \\ &= \frac{2U_{n,m,0}}{\exp(P_0 l)+\exp(-P_0 l)} = \frac{U_{n,m,0}}{ch(P_0 l)} \end{aligned} \tag{20}$$

Let us determine the VT transformation ratio for the *n*-th harmonic:

$$K_{t,n} = \frac{U_{n,m,0}}{U_{n,m,l}} = ch(P_0 l) \tag{21}$$

To obtain a more explicit formula, we simplify the expression of the hyperbolic cosine:

$$P = \sqrt{Z_0 Y_0} = \sqrt{(r_0 + jnx_0)\cdot(g_0 + jnb_0)} = \sqrt{(r_0 + jnx_0)\, jnb_0} = \sqrt{\frac{nb_0}{2}(1+j)}\cdot\sqrt{r_0 + jnx_0}$$

In almost all cases, $g_0 \approx 0$ is assumed. Then, given the following

$$\sqrt{j} = \sqrt{\exp(j90^0)} = \exp(j45^0) = \frac{\sqrt{2}}{2} + j\frac{\sqrt{2}}{2} = \frac{1+j}{\sqrt{2}}$$

and after some transformation, we obtain:

$$P_0 = \sqrt{2nb_0}\cdot\sqrt[4]{r_0^2 + (nx_0)^2}\cdot\left(\frac{r_0 - nx_0}{\sqrt{r_0^2+(nx_0)^2}} + j\frac{r_0 + nx_0}{\sqrt{r_0^2+(nx_0)^2}}\right)$$

Thus, we arrive at:

$$P_0 \cdot l = \sqrt{2nb_0} \cdot \sqrt[4]{r_0^2 + (nx_0)^2} \cdot \left(\frac{r_0 - nx_0}{\sqrt{r_0^2 + (nx_0)^2}} + j \frac{r_0 + nx_0}{\sqrt{r_0^2 + (nx_0)^2}} \right) \cdot l = a_n + jb_n$$

The hyperbolic cosine argument is complex and therefore we can write $ch(P_0 l) = ch(a_n + jb_n)$. After the transformation, we obtain

$$ch(a_n + jb_n) = \sqrt{(ch(a_n) \cdot \cos(b_n))^2 + (sh(a_n) \cdot \sin(b_n))^2} = \sqrt{ch^2(a_n) - \sin^2(b_n)}$$

The VT transformation ratio for the n-th harmonic voltage (current) is finally expressed as follows:

$$K_{t,n} = ch(P_0 l) = \sqrt{ch^2(a_n) - \sin^2(b_n)} \tag{22}$$

where

$$a_n = \sqrt{2nb_0} \cdot \sqrt[4]{r_0^2 + (nx_0)^2} \cdot \left(\frac{r_0 - nx_0}{\sqrt{r_0^2 + (nx_0)^2}} \right) \cdot l = \frac{\sqrt{2nb_0} \cdot (r_0 - nx_0)}{\sqrt[4]{r_0^2 + (nx_0)^2}} \cdot l \tag{23}$$

$$b_n = \frac{\sqrt{2nb_0} \cdot (r_0 + nx_0)}{\sqrt[4]{r_0^2 + (nx_0)^2}} \cdot l \tag{24}$$

Thus, under a non-sinusoidal supply voltage, the VT transformation ratio for the n-th harmonic voltage components can be estimated by formulas (22) – (24) expressed with distributed parameters. As can be seen from these formulas, the expressions are simple and this simplifies the computational procedures.

IV. Modeling results

Calculations were carried out to estimate the transformation ratios for the voltage transformer of type MOM-6, using the obtained formulas (22) – (24). The calculation results are shown in Figure 3. Comparative curves $K_{t,n} = f(n)$ obtained using formulas (1) and (22) show that when estimating the VT transformation ratio using formulas (22) - (24), which are obtained using a VT distributed-parameter circuit, the error of the measuring instruments is significantly reduced, and the accuracy of the electricity metering instruments is increased.

As follows from Figure 3, when using formula (1) (curve 1), significant distortions occur at $n > 15$, and when using formula (2) (curve 2), the error up to the 27th harmonic inclusive can be considered acceptable. At $n > 27$, the error is tens of percent.

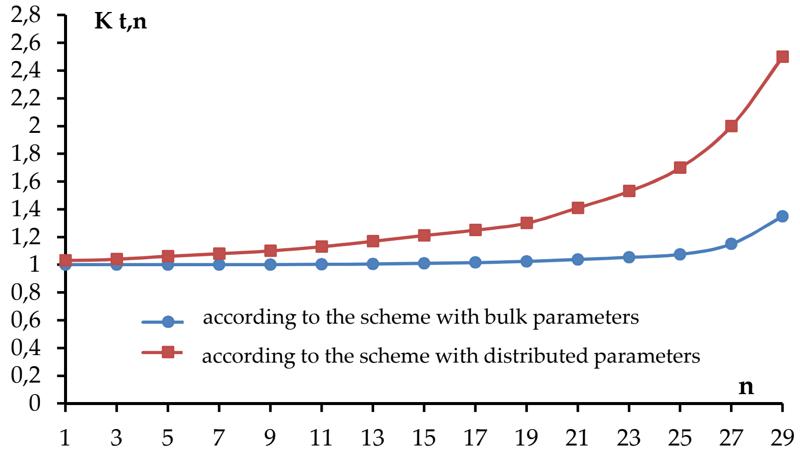

Figure 3: *VT transformation ratio curves for high harmonics*

Figure 4 shows the curve of a change in the relative error of the VT transformation ratio calculated using formulas (1) and (24) depending on the number of harmonics. The comparative analysis of the error indicates that at $n > 11$, the calculation error is more than tens of percent.

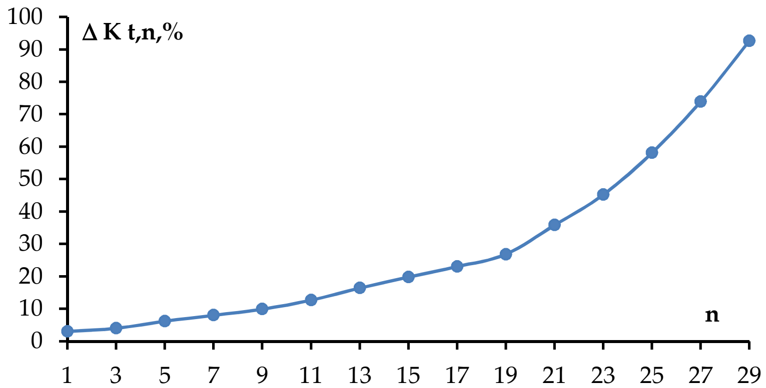

Figure 4: *The curve of a change in the relative error in determining the VT transformation ratio*

Therefore, it is essential to conduct additional research to ensure the reliability of measurements when using instrument transducers.

Conclusion

1. A mathematical model of the transformation ratio is obtained based on a distributed-parameter circuit for the voltage transformer used in the electricity metering system in the presence of harmonic distortion of the supply voltage, which allows boosting the reliability of the calculation and measurement results.

2. The obtained comparative curves suggest that when estimating transformer ratios for the harmonic components of the supply voltage using formulas obtained using a distributed-parameter circuit, the error in the measuring instruments is significantly decreased and the accuracy of the electricity metering instruments is increased. A comparative analysis of the voltage transformer error shows that at $n > 11$, the error in calculation and measurement can amount to more than tens of percent.

3. These findings emphasize the importance of conducting further research to ensure the reliability of measurements using instrument transducers based on instrument transformers.

References

[1] Huanghui Zhang, Haiming Shao, Jiafu Wang. The Research on Additional Errors of Voltage Transformer Connected in Series // Published in: IEEE_Access_(Volume: 8), February 2020, IEEE Access PP(99):1-1, DOI: 10.1109/ACCESS.2020.2972304, Electronic ISSN: 2169 -3536, https://ieeexplore.ieee.org/document/8986609

[2] Maja Grbić, Dragutin Salamon, Jovan Mikulović. Analysis of influence of measuring voltage transformer ratio error on single-circuit overhead power line electric field calculation results// Electric Power Systems Research, Volume 166 , January 2019, Pages 232-240, https://www.sciencedirect.com/science/ article/abs/pii/S0378779618303183

[3] Artemov AI, Andreenkov ES, Errors of measuring voltage transformers with nonlinear loading//Electrical equipment: Exploitation and Repair, No. 3, 2017, https://panor.ru/articles/pogreshnosti-izmeritelnykh-transformatorov-napryazheniya-pri-nelineynoy-nagruzke/50668.html

[4] Andreenkov ES, Artemov AI Utochnenie ergorestei three-winding transformers of voltage // Information technologies, energy and economics. Proceedings of the XII International scientific and technical conference of students and postgraduates. In 3 Volumes, Smolensk: Universum, 2015, P. 6–10.

[5] GOST (State Standard) 30804.4.7–2013. Electromagnetic compatibility of technical means. General guide to measuring instruments and measurements of harmonics and interharmonics for power systems and technical means connected to them. M.: Standartinform. 2013.

[6] R. Ghosh, B. Chatterjee, and S. Chakravorti, Investigations on the effect of voltage harmonics on leakage current for condition monitoring in insulators, in 2016 IEEE 6th International Conference on Power Systems, ICPS 2016, 2016.

[7] B. Singh and V. Verma, An improved hybrid filter for compensation of current and voltage harmonics for varying rectifier loads, Int. J. Electrical Power & Energy Systems., Vol . 29 , No. 4, 2007, pp. 312-321.

[8] B. Suechoey, C. Thammarat , M. Leelajindakraireak. Estimation of core loss of transformer under non-sinusoidal voltage supply // International Conference on Power System Technology, 2004. PowerCon 2004 . Vol.1.

[9] Michal Kaczmarek and Ernest Stano. Application of the Sinusoidal Voltage for Detection of the Resonance in Inductive Voltage Transformers//*Energies* 2021, *14* (21), 7047, pp.1-16, https://doi.org/10.3390/en14217047

[10] Simkin LA, Domanov VF, Avanesov VM, Plahotnyuk AN Experience in operation and verification of measuring transformers of electric energy accounting systems // Industrial Energy, 2000, No. 10, pp. 17-21.

[11] Anders Bergman . Estimation of errors of voltage transformers on-site and the uncertainty of the estimate // Conference on Precision Electromagnetic Measurements. Conference Digest. CPEM 2000 (Cat. No.00CH37031), 14-19 May 2000, Sydney, NSW, Australia, https://ieeexplore.ieee.org/document/851052

[12] Feng Zhou, Peng Zhao, Min Lei, Changxi Yue, Jicheng Yu. Capacitive voltage transformer measurement error prediction by improved long short-term memory neural network// Energy Reports, Volume 8, Supplement 10, November 2022, pp. 1011-1021, https://www.sciencedirect.com/science/article/pii/ S235248472201109X

[13] Guliyev H.B., Sadykhov E.V., Dzhabbarova S.M. Reliability of calculation and measurements of indicators of sinusoidal distortion // Nauchnye Izvestiya, SDD, 2001, No. 4, pp. 77-81.

[14] Guliyev H.B. Evaluation of the transformation coefficient of the voltage transformer during polyharmonic supply voltages // Nauchnye Izvestiya, SDD, 2008, No. 1, pp.94-100.

[15] Andreenkov E.S., Artemov A.I. Estimation of errors of voltage transformers under non-sinusoidal load // Bulletin of the Kuzbass State Technical University, 2016, pp.97-103, https://elibrary.ru/item.asp?id=28963215

[16] Michal Kaczmarek. Measurement error of non-sinusoidal electrical power and energy caused by instrument transformers // *IET Generation, Transmission & Distribution, 2016, 10 (14),* pp.3492 -3498, https://doi.org/10.1049/iet-gtd. 2016.0131

[17] Jayanth R. Ramamurthya, Nicola Chiesa B., Hans K. Høidalenb, Bruce A. Morka, Nils M. Stenviga, Adam C. Mantya. Influence of voltage harmonics on transformer no-load loss measurements and calculation of magnetization curves // Electric Power Systems Research 146 , 2017, p.43–50, https://daneshyari.com/article/preview/5001105.pdf

[18] Jawad Faiz , Milad Ghazizadeh , Hashem Oraee . Derating of transformers under non-linear load current and non-sinusoidal voltage – an overview // IET Electric Power Applications, Volume 9, Issue 7, 2015, pp.486-495, https://doi.org/10.1049/iet- epa.2014.0377

[19] Anh -Tuan Phung, Hoang-Phuong Vu, Trinh-Tuan Nguyen, Dang- Hai Nguyen. Error analysis for inductive current transformers under non-sinusoidal waveform current// The University of Danang - Journal of Science and Technology, 3(124), 2018, pp.49-53, https://media.neliti.com/media/publications/441077-error-analysis-for-inductive-current-tra-cff611bf.pdf

[20] Seyed Reza Karimpour-Mouziraji, Iman Ahmadi-joneidi, Amir Shayegani-Akmal. Evaluation of 3 Phase Dry Transformer under Non-Sinusoidal Load Currents and Unbalanced Voltage Supply//The 23rd International Conference on Electricity Distribution, Lyon, 15-18 June 2015, Paper 0153, p.1-4, http://cired.net/ publications/cired2015/papers/CIRED2015_0153_final.pdf