Predicting the influence of the non-sinusoidal network mode on power transformers

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Abstract. The parameters of electrical network modes often do not meet the requirements of Russian GOST 32144-2013 and the guidelines of Vietnam. In the actual operating conditions while there is the non-sinusoidal mode in electrical networks voltage and current harmonics are present. Harmonics result in overheating and damage of power transformers since they cause additional active power losses. Additional losses lead to the additional heat release, accelerating the process of insulating paper, transformer oil and magnetic structure deterioration consequently shortening the service life of a power transformer. In this regard there arises a need to develop certain scientific methods that would help demonstrate that low power quality, for instance could lead to a decrease in the electrical equipment service life. Currently we see a development of automated systems for continuous monitoring of power quality indices and mode parameters of electrical networks. These systems could be supplemented by characteristics calculating programs that give out a warning upon detection of the adverse influence of voltage and current harmonics on various electrical equipment of both electric power providers and electric power consumers. A software program presented in the article may be used to predict the influence of voltage and current harmonics on power transformers.

1 Introduction

Today, voltage and current harmonics are a major problem of the electrical networks. As a result, the parameters of network modes under actual operating conditions differ from those required for electrical equipment. They do not satisfy the requirements of the Russian state standard [1] nor the Vietnamese guidelines [2, 3]. In [4], it is noted that in Russia "large values of K_U and $K_{U(n)}$ that characterize non-sinusoidal voltage are observed in electrical networks supplying power to the alternating current railway, aluminum smelters and large metallurgical enterprises". The results of $K_{I(n)}$ measurements that characterize non-sinusoidal current in the 110 kV electrical networks of Vietnam [5] showed that they are 2-3 times higher than the standard values [2, 3].

For many years, a considerable attention has been paid to estimating the effect of voltage and current harmonics on power transformers [6-8]. This article provides an overview of the characteristics used to estimate the influence of harmonics on power transformers. Based upon these characteristics a computational program "Prediction of non-sinusoidal mode parameters effect on power transformers" was developed using the Microsoft Excel and Matlab software packages. The program calculates active power losses when voltage is sinusoidal and non-sinusoidal, estimates an increase in losses when voltage is non-sinusoidal and a decrease in the transformer service life and evaluates energy efficiency of the transformer.

This article solves the problem stated in [4] of the need to develop "a common scientific methodology and recommendations that would help assess ...the damage associated with the total service life decrease of energy-consuming devices and equipment of a consumer connected to a network, where the power quality indices do not comply with the requirements of the state standards".

The above-stated characteristics were calculated for the TDTNZh-40000/110 transformer installed at one of the railway substations with the help of the developed computational program. The power quality indices and the non-sinusoidal mode parameters obtained at the railway substation were used as background information for the calculation. The transformer nameplate data as per GOST 51559-2000 are as follows: S_R =40000 kVA, U_R =115 kV, I_R =200 A, P_{NLR} =39 kW, P_{LLR}=200 kW, R_T =1.65 Ohm.

2 Analyzing non-sinusoidal mode in the node of a railway substation connection to the power mains

Fig. 1 shows the oscillograms of voltages and currents for one of the measurements and it is obvious that the shapes of voltage and current curves are non-sinusoidal.

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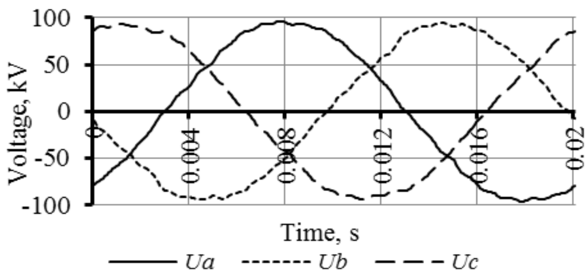
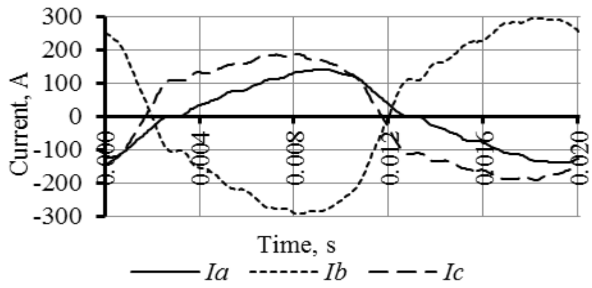


a)



b)

Fig. 1. Oscillograms of phase voltages a) and currents b).

Table 1 contains the measured $K_{U(n)}$ and standard $K_{U(n)95\%}$ values of coefficients of the *n*-th voltage harmonic [1] and the measured values $K_{I(n)}$ of coefficients of the *n*-th current harmonic (for some harmonics). The norms [1] are most often violated at ten harmonics given in the Table. The $K_{U(n)}$ values that are over the limit are shown in bold. The standards were complied with only on the 13-th and 17-th harmonics. The Table shows that the mode is unbalanced. The magnitudes of voltages and currents harmonics are random. The assessments of the voltages and currents harmonics of three phases with a 95% probability will be used to calculate the parameters, which characterize their effect on the transformer under consideration.

Table 1. $K_{U(n)}$ and $K_{I(n)}$, %.

n	3	5	7	9	11	23	25
$K_{U(n)A}$	0.9	**2.0**	1.0	**1.1**	**1.4**	**1.6**	**0.8**
$K_{U(n)B}$	**1.9**	**2.3**	**1.2**	**1.2**	**1.5**	**1.3**	**0.9**
$K_{U(n)C}$	1.2	**2.2**	0.9	**1.0**	**1.6**	**1.3**	**0.9**
$K_{U(n)95\%}$	1.5	1.5	1.0	0.4	1.0	0.4	0.4
$K_{I(n)A}$	12.0	9.9	5.1	2.7	2.9	1.9	1.6
$K_{I(n)B}$	1.6	7.4	3.4	2.7	2.5	1.8	0.9
$K_{I(n)C}$	36.4	9.3	7.1	5.0	2.7	3.0	1.7

3 Active power losses in transformer in non-sinusoidal mode

Harmonics of voltages and currents cause additional active power losses in the transformer. A diagram of losses classification is given in Fig. 2 [7-10].

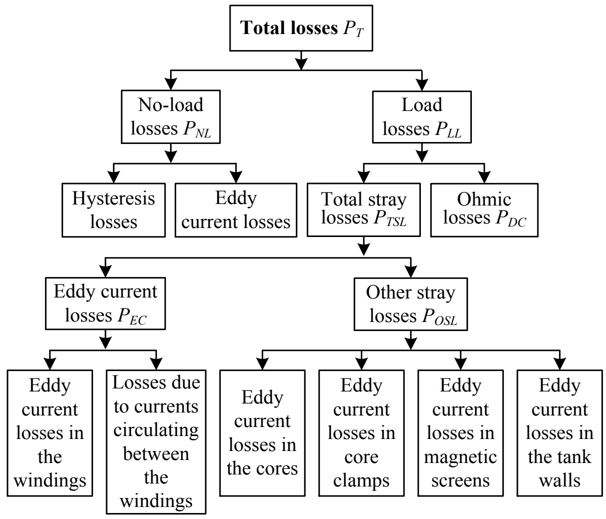


Fig. 2. Classification of active power losses in transformer.

3.1 No-load losses in non-sinusoidal mode

In [9] the transformer no-load losses in the non-sinusoidal mode P_{NL-NS} are calculated using an expression

$$P_{NL-NS} = P_{NLR} \sum_{n=1}^{n_{max}} \left[1/n^{2.6} \left(K_{U(n)}/100 \right)^2 \right], \qquad (1)$$

where n – a number of a harmonic; P_{NLR} – no-load losses of the transformer in the sinusoidal mode, kW; $K_{U(n)}$ – a coefficient of the *n*-th voltage harmonic, %.

Using the expression (1), the no-load losses were calculated for harmonics 2-40 for the $K_{U(n)}$ values with a 95% probability. A screen shot with the calculation results is given in Fig. 3 as the program output. Losses in the non-sinusoidal mode compared with losses in the sinusoidal mode P_{NLR} vary only slightly. The total excess of losses in three phases is 0.8 W.

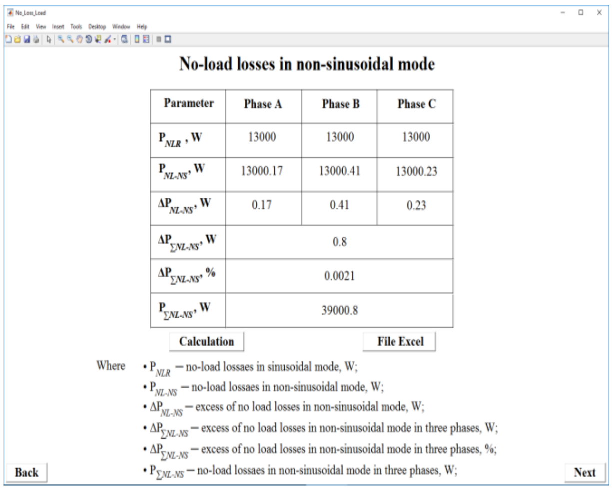


Fig. 3. The calculation result of no-load losses in non-sinusoidal mode.

3.2 Load losses in non-sinusoidal mode

According to the diagram in Fig. 2, load losses in the transformer consist of resistive losses in windings and eddy current losses [6, 8-10].

Resistive losses in windings P_{DC-NS} are determined using the expression

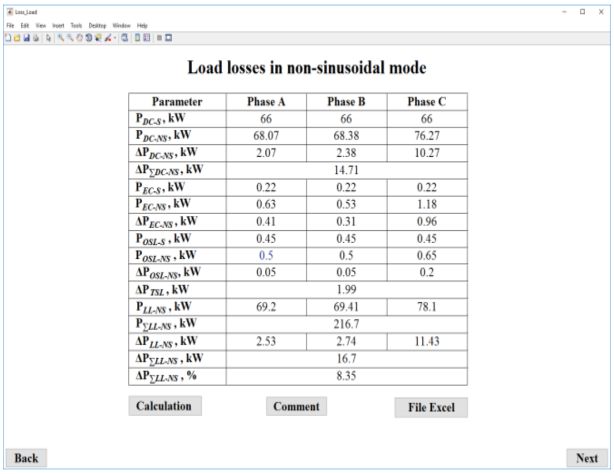
$$P_{DC-NS} = P_{DC-S} \sum_{n=1}^{n_{max}} \left(K_{I(n)} / 100 \right)^2 , \qquad (2)$$

where $P_{DC-S} = R_T I_R^2$ – resistive losses when the current is sinusoidal; R_T – resistance of the transformer winding, Ohm; I_R – the effective value of the transformer winding rated current, A; $K_{I(n)}$ – a coefficient of the *n*-th current harmonic, %.

An increase in active power losses in the non-sinusoidal mode is determined using the expression

$$\Delta P_{DC-NS} = P_{DC-NS} - P_{DC-S} . \qquad (3)$$

Fig. 4 shows the resistive losses in high and medium voltage windings of the considered transformer calculated using the expressions (2, 3). It follows from the Table that the power losses in windings increase by 14.71 kW when the current is non-sinusoidal.


Load losses in non-sinusoidal mode

Parameter	Phase A	Phase B	Phase C
P_{DC-S}, kW	66	66	66
P_{DC-NS}, kW	68.07	68.38	76.27
ΔP_{DC-NS}, kW	2.07	2.38	10.27
$\Delta P_{\sum DC-NS}$, kW	14.71		
P_{EC-S}, kW	0.22	0.22	0.22
P_{EC-NS}, kW	0.63	0.53	1.18
ΔP_{EC-NS}, kW	0.41	0.31	0.96
P_{OSL-S}, kW	0.45	0.45	0.45
P_{OSL-NS}, kW	0.5	0.5	0.65
ΔP_{OSL-NS}, kW	0.05	0.05	0.2
ΔP_{TSL}, kW	1.99		
P_{LL-NS}, kW	69.2	69.41	78.1
$P_{\sum LL-NS}$, kW	216.7		
ΔP_{LL-NS}, kW	2.53	2.74	11.43
$\Delta P_{\sum LL-NS}$, kW	16.7		
$\Delta P_{\sum LL-NS}$, %	8.35		

Fig. 4. The calculation result of load losses in non-sinusoidal mode.

In the non-sinusoidal mode *eddy current losses* P_{TSL} consist of eddy current losses in windings and eddy current losses in other transformer components.

Eddy current losses in windings are calculated using

$$P_{EC-NS} = P_{EC-S} \left[\sum_{n=1}^{n_{max}} n^2 \left(K_{I(n)} / 100 \right)^2 \right], \qquad (4)$$

where $P_{EC-S} = 0.33 \left(P_{LLR} - P_{DC-S} \right)$ – eddy current losses in windings in the sinusoidal mode, P_{LLR} – short-circuit losses in the transformer, kW.

When the current is non-sinusoidal *eddy current losses in other transformer components* are calculated using

$$P_{OSL-NS} = P_{OSL-S} \left[\sum_{n=1}^{n_{max}} n^{0.8} \left(K_{I(n)} / 100 \right)^2 \right], \qquad (5)$$

where $P_{OSL-S} = 0.67 (P_{LLR} - P_{DC-S})$ – eddy current losses in other transformer components in the sinusoidal mode.

Fig. 4 shows eddy current losses in the transformer windings and its other components calculated using the expressions (4, 5). An increase in eddy current losses in the non-sinusoidal mode in contrast to the sinusoidal mode is 1.99 kW.

The total load losses are calculated using

$$P_{LL-NS} = P_{DC-NS} + P_{EC-NS} + P_{OSL-NS} . \qquad (6)$$

The calculated load losses are given in Fig. 4. The above-limit value of load losses in the non-sinusoidal mode in contrast to the sinusoidal mode is 16.7 kW.

3.3 Decrease in the transformer service life

The actual service life of the transformer (T_{RSL}) in the non-sinusoidal mode in [11, 12] is proposed to be determined using the expression

$$T_{RSL} = T_{SSL} / F_{AA} , \qquad (7)$$

where T_{SSL} – the standard service life of the transformer, years; F_{AA} – the transformer aging coefficient, p.u. It is calculated using

$$F_{AA} = e^{\left(\frac{15000}{383} - \frac{15000}{\Theta_H + 273} \right)} , \qquad (8)$$

where Θ_H – the temperature of the hottest point of the windings, °C.

Temperature Θ_H is determined using

$$\Theta_H = \Theta_{TO} + \Theta_g + \Theta_A , \qquad (9)$$

where Θ_{TO} – a temperature increase in the top layers of oil above the ambient temperature, °C; Θ_g – a temperature increase of the hottest conductor point above the oil temperature, °C; Θ_A – the ambient temperature, °C.

Temperature Θ_{TO} is calculated using

$$\Theta_{TO} = \Theta_{TO-R} \left[\left(P_{LL-NS} + P_{NLR} \right) / \left(P_{LLR} + P_{NLR} \right) \right]^{0.8} , \qquad (10)$$

where Θ_{TO-R} – a standard temperature increase in the top layers of oil above the ambient temperature, °C.

Temperature Θ_g is calculated using the expression

$$\Theta_g = \Theta_{g-R} \left[\begin{array}{l} \left(P_{DC-S} + P_{EC-S} K_{EC-NS} \right) * \\ * \sum_{n=1}^{n_{max}} \left(\frac{K_{I(n)}}{100} \right)^2 / \left(P_{DC-S} + P_{EC-S} \right) \end{array} \right]^{0.8} , \qquad (11)$$

where $\Theta_{g-R} = \Theta_W - \Theta_{TO-R}$ – a standard conductor temperature increase relative to the oil temperature, °C; $K_{EC-NS} = \sum_{n=1}^{n_{max}} K_{I(n)}^2 n^2 / \sum_{n=1}^{n_{max}} K_{I(n)}^2$ – a coefficient of eddy current losses in transformer windings, p.u. [8];

Θ_W – a standard winding temperature increase above the ambient temperature, °C.

Fig. 5 shows the background data and the calculation results of the actual transformer service life using the equations (7-11). From Fig. 5 it follows that the non-sinusoidal mode conditions in phase C may result in a 6.98 year decrease in the standard service life of the transformer.

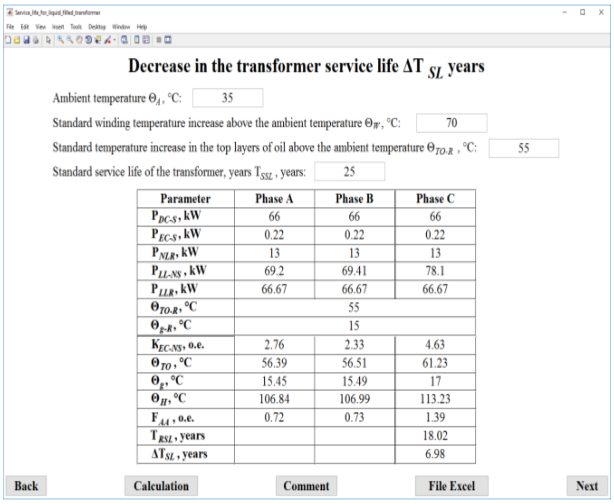


Fig. 5. The calculation result of the actual transformer service life.

3.4 Transformer energy efficiency

Energy efficiency of the transformer is a measure of how much energy is transferred from the transformer primary winding to the secondary. In [13] it is stated that the transformers (η) have a very high efficiency, which reaches 98-99% for most of them. A transformer with high energy efficiency contributes to electric power savings.

In [15, 16], energy efficiency of a transformer is proposed to be assessed using the coefficient

$$\eta_{efficiency} = \frac{100 \beta S_R \cos\varphi}{\beta S_R \cos\varphi + P_{\Sigma NL-NS} + P_{\Sigma LL-NS} \beta^2 T}, \quad (12)$$

where $\beta = (S_{LL} / S_R)$ – a load factor of the transformer; S_{LL} – total measured power of the transformer in three phases, kVA; S_R – rated power of the transformer, kVA; $cos\varphi$ – measured load power factor; $P_{\sum NL\text{-}NS}$ – no-load losses in the non-sinusoidal mode in three phases, kW; $P_{\sum LL\text{-}NS}$ – load losses in the non-sinusoidal mode in three phases, kW; T – a temperature correction factor.

The temperature correction factor T is determined using the expression

$$T = 0.9\left(\frac{R_{T-operat.}}{R_{T-nom.}}\right) + 0.1\left(\frac{R_{T-nom.}}{R_{T-operat.}}\right), \quad (13)$$

where $R_{T\text{-}operat.}$ – resistance of the winding conductors at the operation temperature, Ohm; $R_{T\text{-}nom.}$ – resistance of the winding conductors at nominal temperature, Ohm.

The ratio $\left(\frac{R_{T\text{-}operat.}}{R_{T\text{-}nom.}}\right)$ reflects the change in resistance of the transformer winding conductors following a temperature change caused by the transformer load variation. The change in resistance of the winding conductors is defined using

$$\frac{R_{T\text{-}operat.}}{R_{T\text{-}nom.}} = \frac{1 + \alpha_{20}(\Theta_{H\text{-}average} - 20)}{1 + \alpha_{20}(T_{nom.} - 20)}, \quad (14)$$

where $\alpha_{20} = 0.00393$ – a temperature coefficient of resistance at 20 °C for copper conductors, 1/°C; $\Theta_{H\text{-}average}$ – an average temperature of the hottest point of the transformer windings in three phases, °C; $T_{nom.} = \Theta_A + \Theta_W$ – a nominal operating temperature of the transformer under load, °C.

Taking into account (14), the temperature compensation factor T is converted into

$$T = 0.9\left(\frac{1 + \alpha_{20}\left(\Theta_{H-average} - 20\right)}{1 + \alpha_{20}\left(T_{nom} - 20\right)}\right) + 0.1\left(\frac{1 + \alpha_{20}\left(T_{nom} - 20\right)}{1 + \alpha_{20}\left(\Theta_{H-average} - 20\right)}\right). \quad (15)$$

Fig. 6 provides the background data used to calculate the energy efficiency coefficient of the transformer under consideration and the results of its calculation using (12) with regard to (13-15).

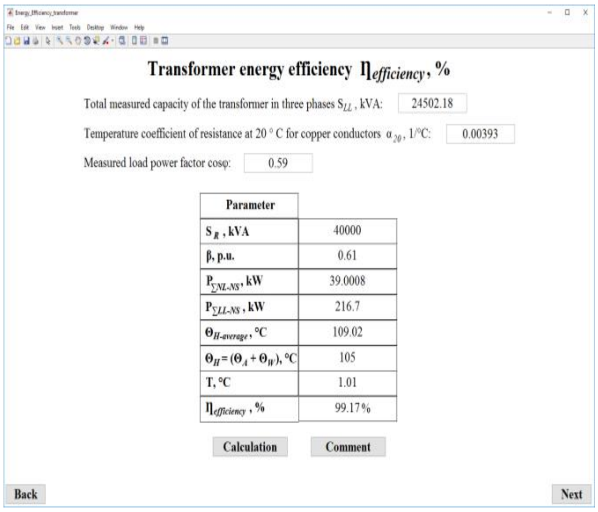


Fig. 6. The calculation result of energy efficiency transformer.

From Fig. 6 it follows that the presence of voltage and current harmonics leads to a decrease in the transformer energy efficiency ratio by 0.48%.

4 Conclusion

1. The calculation results show that the presence of voltage and current harmonics in the input voltages and load currents of the transformer causes additional active power losses in the transformer, which reduce its service life and lead to a decrease in the transformer energy efficiency.
2. At present the work is being carried out to develop the systems of continuous monitoring of electric power quality indicators and electrical network mode parameters, which could be supplemented by performance calculating programs that predict the influence of voltage and current harmonics on various electrical equipment.

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