UDC 621.317.38

https://doi.org/10.33271/nvngu/2021-3/075

O. Bialobrzheskyi[1],
orcid.org/0000-0003-1669-4580,
A. Gladyr[1],
orcid.org/0000-0002-3521-9112,
S. Yakimets[1],
orcid.org/0000-0002-2797-2796,
A. Sulym[2],
orcid.org/0000-0001-8144-8971

1 – Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine, e-mail: seemal@kdu.edu.ua
2 – State Enterprise "Ukrainian Scientific Railway Car Building Research Institute", Kremenchuk, Ukraine

NEED OF TECHNICAL ACCOUNTING AT ELECTRIC ENERGY QUALITY REDUCTION UNDER CONDITIONS OF AC TRACTION SUBSTATION

Purpose. Justification of the need for electrical energy quality technical accounting based on the results of monitoring a 10 kV traction substation transformer mode.

Methodology. Measurements of the current and voltage at secondary busbars of a 10 kV traction substation and monitoring of the electrical energy parameters in the observation interval were carried out. Using the Fourier analysis methods, a current and voltage harmonics level was analyzed. For the current and voltage fundamental harmonic, the positive, negative and zero sequences components are analyzed using the Fortescue transformation. Based on the secondary voltage side current discrete spectrum, the calculation of power loss growth in cable line and transformer windings was carried out.

Findings. As a result of measuring the electrical mode parameters on the transformer secondary voltage busbars, a significant distortion of current and voltage, as well as significant fluctuations in active and reactive power, were established. During the observation interval, significant changes in the power factor are noted. Based on the calculation of additional losses from current higher harmonics in the cable line, it has been established that the current load of the line can be reduced by 10 % while eliminating the current higher harmonics. A similar calculation of loss growth carried out for the traction transformer showed that in the analyzed case its load should not exceed 87.8 % of the nominal one.

Originality. A significant level of harmonic current distortion on secondary voltage busbars of the traction transformer leads to its underutilization, whereas the voltage distortion level, as an electrical energy quality indicator in accordance with current standards, remains within the permissible range. This requires a revision of electrical energy quality indicators, from the standpoint of power, which is due to both current and voltage.

Practical value. The indicators obtained as a result of calculations can be used to correct the load of traction substation transformers. The introduction of the obtained indicators into the set of parameters for electrical energy technical metering is a prerequisite for the development of measures to improve the electrical energy quality.

Keywords: *technical metering, electrical energy quality, traction substation transformer, current and voltage harmonics, power losses*

Introduction. Railway transport complex is a great consumer of electricity, which accounts for about 4 % of total electricity supply in Ukraine. Active electrification of roads leads to a further increase in the share of electricity consumption. Most of the indicated share of electricity consumption is spent on the needs of electric traction. The contact network, which provides energy transmission directly to the electric locomotive, is powered by a traction substation. As a rule, transformers of AC traction substations provide reduction of primary voltage of 110(220) kV district electric networks. In the case of supply of main electric locomotives, the voltage is transformed to the level of 27.5 kV AC. However, DC traction substations are also in operation. Their voltage is transformed to the level of 6(10) kV with subsequent conversion to the constant level of 3.3 kV. At the same time, transformers of traction substations can have windings of medium voltage of 35 kV for non-traction consumers. Traction substations with a secondary voltage level of 6(10) kV have become widespread among the enterprises of the mining complex [1].

The modes of movement of the electric rolling stock, the number of units, the profile of the rail track, and the structure of the traction electric drive form a complex load on the traction power supply system. These factors significantly affect the characteristics of traction transformers, especially at the mining enterprises, where the electric rolling stock operates under difficult conditions.

Literature review. Locomotives of electric rolling stock operating on the electrified railway have various systems of the traction electric drive. Electric locomotives with the following structure of the electric drive: rectifier (network-driven inverter) – DC motor or frequency converter – induction motor – are the most common electric locomotives at alternating current electrified railways [1].

These electric drives cause higher harmonics of current and voltage in the traction power supply system during the electric locomotive operation [2]. The research on the modes of such systems in operation makes some scientists [3] conclude that the assessment of electricity quality is becoming not only a computational tool for designing and planning traction power systems, but also an indispensable method for utilities in terms of accurate assessment of the quality of electricity from railway systems.

The complexity of the formation of the load on the traction power supply system is caused by the simultaneous processes of electric locomotives movement and electric drives regulation. Researchers [4] note that the spectral analysis of traction voltages and currents is the basis for assessing the level of electromagnetic compatibility and quality of power consumption in electric transport systems. Carrying out such an analysis is complicated by the fact that electric locomotives operate in nonstationary dynamic modes. A solution to these difficulties is proposed in paper [5]. The introduction of the concepts of current and instantaneous spectra enables the spectral voltage analysis not only in steady modes but also in transient ones. It is stated that the method of discrete Fourier transform can be fully applied to determine the current and instantaneous spectra.

Measures have been developed and solutions are being implemented to improve the quality of electricity in the traction power supply system.

The use of so-called four-square converters with pulse control in the traction drive system of electric locomotives [6] makes it possible to eliminate the problem of increased harmonic distortions in the supply networks of traction substations. Such a decision requires large-scale modernization of electric locomotives, which is extremely difficult under the current economic conditions. A smaller but no less positive effect can be achieved by using filtration schemes, including active ones, directly in the structure of traction substations [7]. As a result, the quality of the electricity supplied to electric rolling stock is improved. The required level of electromagnetic compatibility of the traction network with the systems of railway automation and communication is achieved.

Obviously, it is impossible to completely exclude the influence of electric rolling stock as a consumer of the traction power supply system. In addition, it is proposed to include a certain assessment of power in the traction power supply system and its consideration in tariffs in the system of rating assessments of the state of energy security when paying for electricity [8] In this regard, there are tasks to assess energy consumption in the presence of distortion. In [9] it is noted that the active power is transmitted not only by the main component (DC or AC), especially in electrified railways. As a result, two indices are proposed for preliminary assessment of the relevance of harmonic active power conditions for 3 kV DC and 2 × 25 kV AC systems.

However, for all the diversity of views on the issue related to the quality of electricity in traction power supply systems, this problem in terms of measuring power or its components is considered only by some researchers [3, 9]. At the same time the distortions of power and electric energy are not taken into account. The above tasks are extremely relevant for traction networks of mining enterprises. Given the relatively simple structure and complexity of power consumption modes, their traction substations require special attention.

Purpose. Substantiation of the need for technical accounting of electricity quality based on the results of monitoring the 10 kV traction substation transformer mode.

Results. OPE-1A electric locomotives, which receive power from the 10 kV AC traction power supply system, are the most widespread on the network of quarry railways [1]. The electric locomotive is equipped with an ODCE-8000/10 transformer with a rated capacity of 7338 kilovolt-amperes.

Two traction windings, each of which is divided into four sections, are designed for a rated voltage of 1900 V, the windings of their own needs – for a voltage of 250, 400 and 625 V. The main controller ECG-21D located above the power transformer is used for current-free switching of its secondary winding. Two VPB-6000 rectifier-converter units with B2-320 diodes and T2-320 thyristors allow smooth changing of the rectified voltage by means of the BU39D control unit. Thyristor voltage is smoothly regulated within each of the four zones by changing the opening angle of the thyristors included in the split arms of the bridges of the rectifier-conversion unit. Direct and reverse transitions between zones are possible in the absence of switching current of the contacts of the main controller. The electric locomotive also provides an automatic transition to self-excitation in the event of an emergency power outage.

Thus, the electric locomotive provides smooth regulation of the traction mode from the technological position, and a complex mode of electricity consumption from the other one.

When calculating the power supply systems of quarry railway electric transport, the circuit is considered, a fragment of which is presented in Fig. 1. The circuit includes load (electric locomotive or several electric locomotives (OPE)), contact network (CN), traction substation transformer (TV) and district high voltage network. The traction complex of the electric locomotive is represented by a transformer (T), thyristor-diode converter (TC) and traction motors (DCM). Due to the complexity of the power consumption mode of the traction train, the research on electrical parameters on the secondary voltage busbars of the transformer TDN-16000/110 traction substation (measuring point) of the mining enterprise was carried out. The Fluke 434 measuring instrument was used to control and record the electrical parameters of the mode.

Flukeview power quality analyzer profile software was used to process the measurement results. Under the condition of recalculation of indicators, the transfer coefficients and circuits of measuring transformers connected to secondary voltage buses are taken into account: 10 kV – 2NOM-10 voltage transformers; 10 kV current transformers TSHL-10 2000/5.

Fig. 2 contains the timing diagrams of voltage and current on the secondary voltage busbars of the transformer of the traction substation. There is a voltage distortion and significant current distortion. Obviously, the distortions are caused by the switching processes of the rectifier units of electric locomotives. This is evidenced by the difference in the shape of the phase currents, the presence of steep fronts at certain intervals, which correspond to the switching intervals of the valves. As a result, voltage pulses occur.

Energy consumption during the day in the researched unit is characterized by significant changes due to the modes of movement of the electric rolling stock. Changes in active power consumption from minimum to maximum value are shown in Table 1. Total active power P_s during the observation period varies in the range from 0.1 to 13 % of the set capacity of the transformer of the traction substation. The active power varies in phases over a wide range, the limit values of which differ for different phases, i. e. there is asymmetry. Fixing the negative values of the active power by phases should be emphasized. The traction complex of electric locomotives cannot implement the recovery mode. Thus, the negative values of the active power by phases are caused by both the phenomenon of asymmetry and the presence of higher harmonics of current and voltage.

Periodic overcompensation for reactive power by phases and in general is determined. In particular, in terms of total reactive power, the overcompensation ranges from –11 % to –2 % (Table 1).

As a result of the mentioned distribution of active and reactive powers, the power factor *cos*j has a complex form in

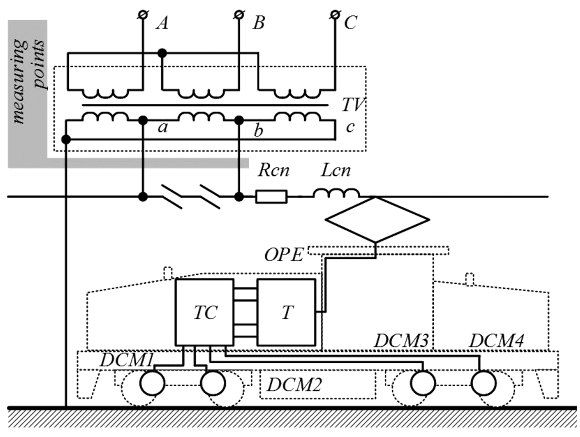
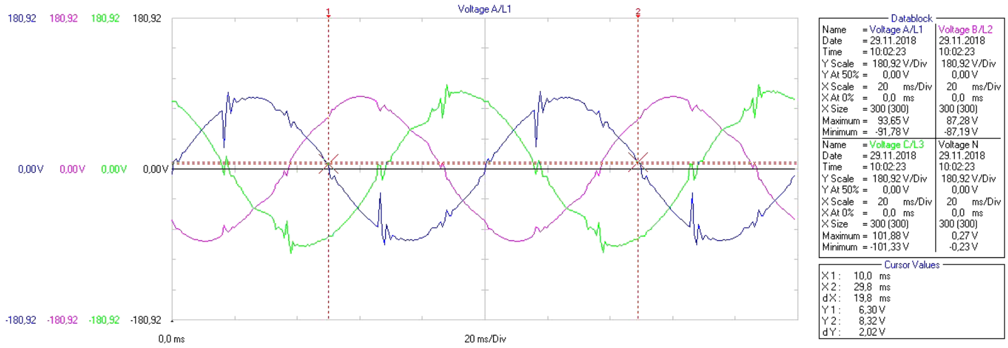
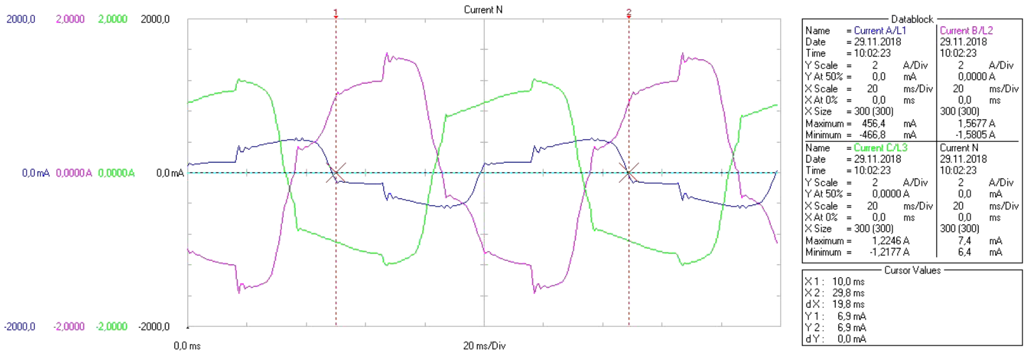


Fig. 1. A simplified circuit-fragment of the traction complex



a



b

Fig. 2. Voltage (a) and current (b) time diagrams of the traction substation transformer on the secondary voltage busbars

Table 1

Researched unit integral indices

	P_a, kW	P_b, kW	P_c, kW	P_s, kW
max	1296	1184	410.5	2159
min	–11.2	–137.5	–151.2	22.4
	Q_a, kVAr	$Q_в$, kVAr	Q_c, kVAr	Q_s, kVAr
max	134.4	332	–5.6	–35.2
min	–512.8	–1113	–1082	–1818
	U_a, kV	$U_в$, kV	U_c, kV	
max	10.78 (8 %)	10.89 (9 %)	11.37 (14 %)	
min	10.11 (1 %)	9.21 (–8 %)	9.91 (–1 %)	
	$\cos\varphi_a$	$\cos\varphi_b$	$\cos\varphi_c$	
max	0.99	0.99	0.71	
min	–0.45	–0.29	–0.34	

time – Fig. 3. The analysis of the minimum and maximum values of the power coefficient reveals that the set power of the existing compensation devices provides a high power factor at some intervals at the level of 0.99 (Table 1), but at certain intervals the power factor falls below zero.

This fact has negative consequences – high voltage and its significant fluctuations. In particular, the c phase voltage in certain intervals exceeds the maximum allowable value of 10 % and is 14 %. Voltage deviations in other phases do not exceed the maximum allowable value.

For certain points in time, the level of current distortion is fixed. Its harmonic composition is shown in Fig. 4. The total voltage distortion coefficient was 2.1 % at the time of fixation, which corresponds to the quality standards of electricity. There is a significant level of current distortion of 58.3 % (Fig. 4); the level of the fifth harmonic exceeds the level of the third one. Current distortions cause voltage distortions that reach the following values in phases $THD_{Ua} = 7.42$ %; $THD_{Ub} = 5.56$ %; $THD_{Uc} = 6.46$ %.

Due to the connection circuit of the secondary winding of the traction transformer to the contact network, there is a significant current asymmetry (Fig. 5) which reaches the value of 82.5 % in reverse sequence.

This situation with current asymmetry leads to voltage asymmetry in the reverse sequence $K_{2U} = 1/8$ %, and in the zero sequence $K_{0U} = 6.1$ %.

Thus, additional heat caused by losses from currents of higher harmonics in the phase conductors is added to the heat released during the flow of the fundamental frequency current proportional to the loss of active power.

The main source of heating of the power cable, as mentioned above, is the loss of current-carrying conductors with resistance $(R_{c_{\approx}})$ under the influence of the acting value of current (I), flowing in them

$$P_c = R_{c_{\approx}} \cdot I^2. \quad (1)$$

At alternating current additional losses are created, both in the conductive core, and in an insulating layer, and in protective metal covers. Additional losses in the cable cores at non-sinusoidal current are created due to the effect of current displacement. In multicore cables there is an additional increase in resistance compared with DC resistance caused by the effect of proximity due to the influence of the cores on each other [10].

The electrical resistance of the core per unit length of cable at direct current is determined by the following formula [11]

$$R_c = \frac{(1+k_0)\cdot \ell \cdot \rho_{20}}{S_c} \cdot \left(1+\alpha_{20}\left(T_c - 20\right)\right), \quad (2)$$

where ρ_{20} is core material specific electrical resistivity at 20 °C, l is core length; S_c is core cross section area; α_{20} is temperature coefficient of increase in the core material resistance; T_c is core maximum operating temperature; k_0 is the twist factor, taking into account the length of the wires from which the core is twisted (values from 0.03–0.05).

Additional power from higher harmonic currents

$$P_h = I_h^2 \cdot R_h, \quad (3)$$

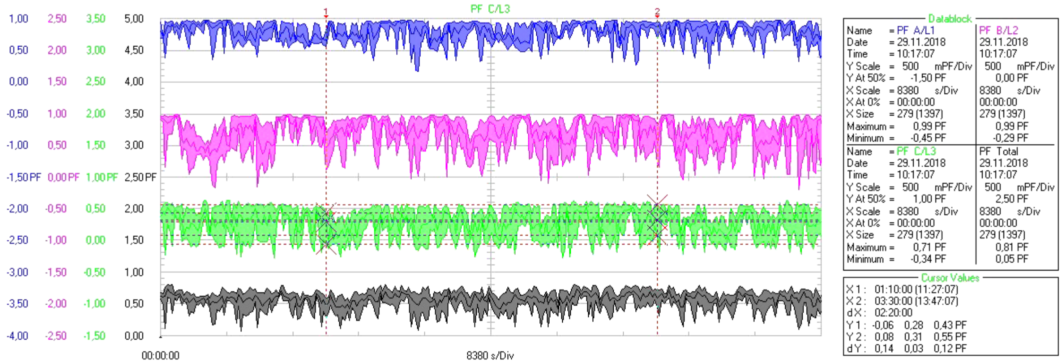


Fig. 3. The power factor change time diagram of the traction substation transformer on the secondary voltage busbars

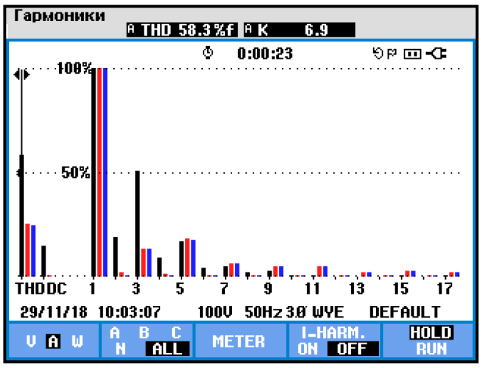


Fig. 4. Current harmonics

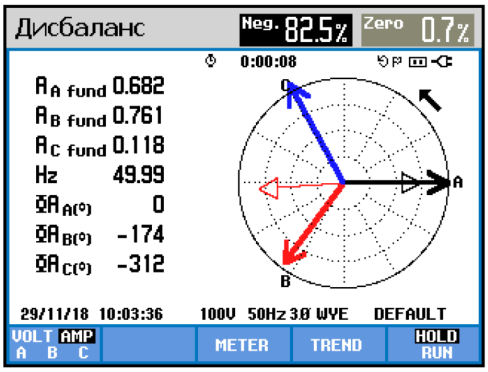


Fig. 5. Current asymmetry

where I_h is the h^{th} harmonic root-mean-square current value; R_h is the core active resistance at the h^{th} harmonic for $h \geq 3$, is determined by formula [11]

$$R_h = R_c\left(0.187 + 0.532 \cdot \sqrt{h}\right)\left(1 + y_s\right), \tag{4}$$

where y_s is the coefficient that takes into account the skin-effect of current displacement and proximity of cores.

For three- and four-core cables, it is determined by formula [11]

$$y_s = \frac{x_s^4}{192 + 0.8\breve{o}_s^4}\left(\frac{d_c}{r}\right)^2 \left[\frac{1.18}{\dfrac{x_s^4}{192 + 0.8\breve{o}_s^4} + 0.27} + 0.312\left(\frac{d_c}{r}\right)^2\right],$$

where r is the distance between the core axes, d_c is the core diameter.

$$x_s^2 = \frac{8 \cdot \pi \cdot f \cdot p}{R_{c\approx}} \cdot 1.159 \cdot 10^{-4}.$$

Thus, when non-sinusoidal current flows through the phase core, power loss is as follows

$$P_{\Sigma}^{phase} = I_1^2 \cdot R_1 + \sum_h I_h^2 \cdot R_h. \tag{5}$$

As a result, it is possible to determine the equivalent phase sinusoidal current (thermal equivalent) in the absence of distortion

$$I_{eq} = \sqrt{\frac{P_{\Sigma}^{phase}}{R_1}}. \tag{6}$$

10 kV electricity is transferred via a copper three-wire cable to the distribution device of the contact network. The parameters of one core of the cable are as follows: length $l = 1100$ m; cross section area $S = 400$ mm^2 the cable rated current $I_{nom} = 880$ A when laid in the ground. Core diameter $d_c = 22.57$ mm; distance between the core axes $r = 33.85$ mm. The results of calculations of the active resistance of the cable cores are given in Table 2.

Table 3 contains the results of the calculation of the two variants: the first variant – according to the data obtained during the experiment (Fig. 4) and the acting value of current $I_{rms} = 510$ A; the second one – according to the distribution of harmonics recorded in the experiment (Fig. 4) and rated acting value of current $I_{rms} = 880$ A.

We can conclude by the results of the analysis of Table 3 that, due to the action of higher harmonics, the line is loaded by 9.6 % more equivalent current. In this case, as proved in [12], it is also rational to take into account the components of the power transmitted by the line.

The decrease in the throughput of the transformer due to non-sinusoidal currents is determined by the increase in additional losses from currents of higher harmonics. The transformer, in contrast to the cable, is more complex electrical equipment in which the losses of active power are concentrat-

Table 2

The values of the phase core active resistance for current h^{th} harmonic

h	1	3	5	7
I_h, %	100	22	34.5	12.3
I_h, A	468.986	103.177	161.8	57.685
R_h, Ohm	0.066	0.072	0.089	0.104

Table 3

Tabulated calculation results

I_{rms}, A	I_1, A	I_3, A	I_5, A	I_7, A	P_{Σ}^{phase}, kW	I_{eq}, A
510	468.986	103.177	161.8	57.685	20.61	558.992
880	809.23	178.031	279.184	99.535	61.38	964.535

ed not only in the windings, but also in other structural parts due to the action of an alternating electromagnetic field.

Losses from eddy currents ($P_{win.h}$) [13] increase in proportion to the square of the load current and are proportional to the square of the frequency. Losses from eddy currents due to higher harmonic currents can be found as follows

$$P_{win.h} = P_{win.nom} \sum_{h=2}^{h=h_{\max}} \left(\frac{I_h}{I_{nom}} \right)^2 \cdot h^2, \tag{7}$$

where $P_{win.nom}$ is losses in the winding from eddy currents under rated conditions; h is the harmonic number; I_h is the root-mean-square value of the current harmonic h; I_{nom} is the root-mean-square value of the fundamental harmonic current and rated load conditions.

Subsequently, the coefficients of increase in eddy current losses in the windings ($K_{win.h}$), eddy current losses in the magnetic core ($K_{mc.h}$) and additional losses in the structural parts of the transformer ($K_{con.h}$) are introduced

$$K_{win.h} = \frac{P_{win.h}}{P_{win.nom}} = \sum_{h=2}^{h=h_{\max}} \left(\frac{I_h}{I_{nom}} \right)^2 \cdot h^2; \tag{8}$$

$$K_{mc.h} = \frac{P_{mc.h}}{P_{mc.nom}} = \sum_{h=2}^{h=h_{\max}} \left(\frac{I_h}{I_{nom}} \right)^2 \cdot h^{1.05}; \tag{9}$$

$$K_{con.h} = \frac{P_{con.h}}{P_{con.nom}} = \sum_{h=2}^{h=h_{\max}} \left(\frac{I_h}{I_{nom}} \right)^2 \cdot h^{0.8}. \tag{10}$$

The introduced coefficients of increase in losses due to currents of higher harmonics will make it possible to write down the equation of losses in the following form

$$\Delta P_h = K_{win.h} \cdot P_{win.nom} + K_{mc.h} \cdot P_{con.nom} + K_{com.h} \cdot P_{con.nom}. \tag{11}$$

The equivalent load capacity of the transformer is determined on the basis of the equality of active power losses in the rated mode (ΔP_{nom}) and in the presence of current harmonics (ΔP_h). At the same time the increase in losses of idling from higher harmonics of current is neglected because of their small influence on idling losses.

As a result of increasing the equivalent current [14]

$$\frac{I}{I_{nom}} = \sqrt{\frac{\Delta P_{nom}}{\Delta P_{nom} + K_{win.h} \cdot P_{win.nom} + K_{mc.h} \cdot P_{con.nom} + K_{con.h} \cdot P_{con.nom}}}. \tag{12}$$

The equation shows by what value the root-mean-square value of the current should be reduced in the presence of higher harmonics of the current relative to the rated current of the transformer.

We perform the calculation for the studied mode, according to the level of higher harmonics of the current (Fig. 4) the coefficients of increase in losses are presented in Table 4.

Transformer TDN-16000/10 has rated power S_N = = 16 000 kVA; rated voltage U_{HV} = 158 kV; U_{LV} = 11 kV; short circuit voltage U_{SC} = 11 %; losses ΔP_{IM} = 19 kW; ΔP_{SC} = 88 kW; idle current I_{IM} = 0.8 %.

The parameters of the equivalent circuit $X_T = \frac{U_{SC}\ \%}{100} \frac{U_{HV}^2}{S_N} = 171.413$ Ohm; active resistance $R_T = \frac{\Delta P_{SC}}{S_N} \frac{U_{HV}^2}{S_N} =$ = 8.581 Ohm; active conductivity $G_T = \frac{\Delta P_{IM}}{U_{HV}^2} = 0.76 \mu S$; reactive conductivity $B_l = \frac{I_{IM}}{100} \frac{S_N}{U_{HV}^2} = 5.127 \mu S$.

Losses in the winding taking into account eddy currents in it under rated conditions $\Delta P_{win.nom}$ = 32.31 kW; losses from eddy currents in the core $\Delta P_{mc.nom}$ = 19 kW; losses in the structural parts of the transformer $\Delta P_{con.nom}$ = 363.957 W.

Taking into account the specified levels of losses and the coefficients of growth of losses given in Table 4, the operating current of the transformer should make, p.u.

$$\frac{I}{I_{nom}} = 0.878.$$

Thus, due to the action of higher harmonic currents, the losses in the transformer are increased, without taking into account the factor of the connection scheme of the transformer windings, which can cause a significant increase in losses from current harmonics multiples of three.

Voltage harmonics whose level is significantly lower than the level of current harmonics in this case are not taken into account. However, the influence of these harmonics on the losses in the magnetic circuit of the transformer should not be excluded. In this case, if we rely on the current standards of electricity quality [15], in particular the voltage, the quality of electricity at the object under study is normal except in rare cases.

Knowledge of the observed impact, in this case, and its calculation provide a certain assessment of energy processes from the standpoint of losses. Accordingly, they contribute to the formation of recommendations for the loading of the transformer, cable line and their subsequent operation. It should be borne in mind that the current spectrum, its asymmetry and similar voltage characteristics change over time. Thus, the electric energy is accounted only on active and reactive capacities. Obviously, electricity quality cannot be measured by reactive power alone. This makes it impossible to take into account the quality of electricity in terms of higher harmonics, current and voltage asymmetry [16].

As a result, there is a need to modernize the existing system of automated control and metering of electricity. The procedure can be implemented by additional input of power components or corresponding indicators that reflect the degree of violation of the quality of electricity, for example, as performed in [16, 17]. Accordingly, there is a need to formulate integrated indicators, which in combination with active and reactive power will be determined, registered. The order of direct or indirect accounting of these indicators is no less important task.

Conclusions.

1. As a result of measurements of electrical parameters of the mode on the secondary voltage busbars of the transformer, significant current and voltage distortions were found, additional losses from which require a 10 % reduction in the load of the transmission line and the traction substation transformer by 12.2 %.

2. The level of voltage distortion, as an indicator of the quality of electricity in accordance with current standards, remains within acceptable limits. Significant level of harmonic current distortion on the secondary voltage busbars of the traction transformer leads to its underutilization. Thus, the regulated indicators of electricity quality need to be revised from the standpoint of power, which is determined by both current and voltage.

3. The introduction of the indicators used in the research to a set of parameters of electricity technical accounting is a prerequisite for the development of measures to improve the quality of electricity.

Table 4

The calculating results of the increasing loss coefficients

h	I_h p.u.	I_h^2 p.u.	h^2	$h^{0.8}$	$h^{1.05}$	$I^2 \cdot h^2$ p.u.	$I^2 \cdot h^{0.8}$ p.u.	$I^2 \cdot h^{1.05}$ p.u.
1	1.000	1.000	1.00	1.00	1.000	1.000	1.000	1.000
3	0.220	0.048	9.00	2.41	3.169	0.436	0.117	0.153
5	0.045	0.002	25.00	3.62	5.419	0.051	0.007	0.011
7	0.020	0.000	49.00	4.74	7.715	0.020	0.002	0.003
Sum		1.051	–	–	–	1.506	1.126	1.167

4. The development of methods for technical accounting of electricity quality by power components, which will complement the active and reactive power, will become topical in the future.

References.

1. Ogunsola, A., & Mariscotti, A. (2013). Railway Traction Systems. In: Electromagnetic Compatibility in Railways. *Lecture Notes in Electrical Engineering, Springer, Berlin, Heidelberg, 168.* https://doi.org/10.1007/978-3-642-30281-72.

2. Tao, H., Hu, H., Jiang, X., He, Z., & Zhao, C. (2016). Research on low frequency voltage oscillation in traction power supply system and its affecting factors. *Dianwang Jishu/Power System Technology*, *40*(6), 1830-1838. https://doi.org/10.13335/j.1000-3673.pst.2016.06.033.

3. Hu, H., He, Z., Wang, K., Ma X., & Gao, S. (2016). Power-Quality Impact Assessment for High-Speed Railway Associated With High-Speed Trains Using Train Timetable – Part II: Verifications, Estimations and Applications, *IEEE Transactions on Power Delivery, 31*(4), 1482-1492. https://doi.org/10.1109/TPWRD.2015.2472961.

4. Szelag, A., Kostin, M., Nikitenko, A., Mishchenko, T., & Jefimowski, W. (2019). Development of a Spectral Theory for Analysis of Non-Stationary Pulse Stochastic Electromagnetic Processes in Devices of Electric Transport Systems. *2019 IEEE 6th International Conference on Energy Smart Systems (ESS).* https://doi.org/10.1109/ess.2019.8764205.

5. Kostin, N. A., & Sheikina, O. G. (2016). Development of the theory of spectra of stochastic processes of voltages and currents of electric transport systems, *Electromagnetic compatibility and safety on railway transport*, (12), 11-18.

6. Kryukov, A. V., Cherepanov, A. V., Shafikov, A. R., & Bezridnyj, E. S. (2019). Simulation of non-sinusoidal modes in railway power supply systems during movement of high-speed trains IOP Conference Series: *Materials Science and Engineering, International Conference on Transport and Infrastructure of the Siberian Region (SibTrans-2019) 12–15 November 2019*, *760*, 1-8. https://doi.org/10.1088/1757-899X/760/1/012034.

7. Shcherbak, Y. V., & Semenenko, Yu. A. (2016). Analysis of the functioning of a combined active filter of a sequential type with selective links for direct current traction substation. *Energetika. Proceedings of CIS higher education institutions and power engineering associations*, *59*(5), 418-426. https://doi.org/10.21122/1029-7448-2016-59-5-418-426.

8. Bondarenko, V., Domanskyi, I., & Kostin, G. (2017). Analysis of energy efficiency of operating modes of electrical system with the traction loads. *Electrical Engineering & Electromechanics,* (1), 54-62. https://doi.org/10.20998/2074-272X.2017.1.09.

9. Mariscotti, A. (2019). Relevance of Harmonic Active Power Terms for Energy Consumption in Some Railway Systems (Version 05). *Presented at the 24nd IMEKO TC4 International Symposium Electrical & Electronic Measurements, Xi'An, China: Zenodo.* https://doi.org/10.5281/zenodo.3604338.

10. Zhezhelenko, I. V., Saenco, Yu. L., Baranenko, T. K., Gorpinich, A. V., & Nesterovich, V. V. (2007). *Selected issues of non-sinusoidal modes in electrical networks of enterprises: monograph*. Energoatomizdat. Retrieved from http://eir.pstu.edu/handle/123456789/5417.

11. Milardovich, N., Prevosto, L., & Lara, M. A. (2014). Calculation of harmonic losses and ampacity in low-voltage power cables when used for feeding large LED lighting loads. *Advanced Electromagnetics*, *3*(1), 50-56. https://doi.org/10.7716/aem.v3i1.258.

12. Bialobrzheskyi, O., & Rod'kin, D. (2020). Apparent power effectiveness for the assessment of the efficiency of the cable transmission line in the supply system with sinusoidal current (Ocena strat w linii przesyłowej kablowej w systemie zasilania prądem sinusoidalnym). *Przeglad Elektrotechniczny, 96*(9), 26-29. https://doi.org/10.15199/48.2020.09.05.

13. López-Fernández, X. M., Bülent Ertan, H., & Turowski, J. (2017). *Transformers: Analysis, design, and measurement*, (pp. 1-609). CRC Press. https://doi.org/10.1201/b12275.

14. Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). *Introduction to Industrial Energy Efficiency*. Academic Press. https://doi.org/10.1016/C2018-0-01452-8.

15. *DSTU EN 50160:2014 (EN 50160:2010, IDT) National standard of Ukraine. Characteristics of the power supply in the electrical framing of the intrinsic value* (n.d.). Kyiv: Minenergorozvitku Ukrainy. https://www.en.lg.ua/images/stories/2019/standart-yakosti.pdf.

16. Bialobrzheskyi, O., & Rodkin, D. (2020). The assessment of the distortion of electric power in alternating and pulse current of a rectifier circuit (Analiza zniekształcenia mocy w obwodzie z prostownikiem). *Przeglad Elektrotechniczny, 96*(8), 118-121. https://doi.org/10.15199/48.2020.08.23.

17. Bialobrzheskyi, O. V., & Rod'kin, D. Y. (2019). Distorting electrical power of the alternating current in the simplest circuit with a diode. *Energetika. Proceedings of CIS Higher Education Institutions and Power Engineering Associations*, *62*(5), 433-444. https://doi.org/10.21122/1029-7448-2019-62-5-433-444.

Необхідність технічного обліку зниження якості електричної енергії в умовах тягової підстанції змінного струму

О. В. Бялобржеський[1], *А. І. Гладир*[1], *С. М. Якимець*[1], *А. О. Сулим*[2]

1 – Кременчуцький національний університет імені Михайла Остроградського, м. Кременчук, Україна, e-mail: seemal@kdu.edu.ua

2 – Державне підприємство «Український науково-дослідний інститут вагонобудування», м. Кременчук, Україна

Мета. Обґрунтування необхідності технічного обліку якості електричної енергії за результатами моніторингу режиму трансформатора тягової підстанції 10 кВ.

Методика. Проведено вимірювання струму й напруги на шинах вторинної напруги тягової підстанції 10 кВ і моніторинг параметрів електричної енергії на проміжку інтервалу спостереження. Із використанням методів Фур'є аналізу виконано аналіз рівня гармонік струму й напруги. Для основної гармоніки струму й напруги з використанням перетворення Фортеск'ю проведено аналіз складових прямої, зворотної та нульової послідовностей. На підставі дискретного спектра струму на стороні вторинної напруги проведено розрахунок зростання втрат потужності в кабельній лінії та обмотках трансформатора.

Результати. У результаті проведених вимірювань електричних параметрів режиму на шинах вторинної напруги трансформатора встановлено істотне спотворення струму й напруги, а також значні коливання активної та реактивної потужності. На інтервалі спостереження відзначаються значні зміни коефіцієнта потужності. На підставі розрахунку додаткових втрат від вищих гармонік струму кабельної лінії встановлено, що струмове навантаження лінії може бути знижене на 10 % при усуненні вищих гармонік струму. Аналогічний розрахунок зростання втрат, проведений для тягового трансформатора, показав, що в аналізованому випадку його навантаження не повинне перевищувати 87,8 % від номінального.

Наукова новизна. Істотний рівень гармонійних спотворення струму на шинах вторинної напруги трансформатора тягової підстанції призводить до його недовикористання, при цьому рівень спотворень напруги, як показник якості електричної енергії відповідно до чинних стандартів, залишається в допустимих межах. Це вимагає перегляду показників якості електричної енергії з позиції потужності, що обумовлена як струмом, так і напругою.

Практична значимість. Використані в роботі показники та їх чисельні значення можуть бути застосовані для корекції навантаження трансформаторів тягових підстанцій. Уведення отриманих показників до комплексу параметрів технічного обліку електричної енергії є передумовою для розробки заходів щодо підвищення якості електричної енергії.

Ключові слова: *технічний облік, якість електричної енергії, трансформатор тягової підстанції, гармоніки струму й напруги, втрати потужності*

Recommended for publication by O. P. Chornyi, Doctor of Technical Sciences. The manuscript was submitted 25.01.21.