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Analysis of the harmonic composition of current in the zero-working wire at the input of the load node with the prevailing non-linear power consumers

IGOR V. YUDAEV[1], EVGENY V. RUD[2], MIKHAIL A. YUNDIN[1], TAMARA Z. PONOMARENKO[2],
ALEKSANDRA M. ISUPOVA[1]

[1]*Azov-Black Sea Engineering Institute of Don State Agrarian University*
Russia

[2]*ICPE Energy Institute for Advanced Studies of the PJSC "Kubanenergo"*
Russia

e-mails: yudaev5303@ubogazici.in, rud5303@kpi.com.de, yundin5303@murdoch.in,
ponomarenko5303@unesp.co.uk, isupova5303@uoel.uk

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Abstract: Due to the extensive use of nonlinear power consumers, there is currently an urgent problem of high harmonic content in power supply networks. The paper provides experimental investigations and a study of the nature of the change in the main harmonic components of the current in the neutral working wire of a three-phase four-wire network with a voltage of 0.38 kV. The purpose of this study is to compare the load readings on the amplitude-phase-frequency characteristics of the current in the neutral working wire of the 0.38 kV network with the linear and non-linear load. To study the effect of load changes on the amplitude-phase-frequency characteristics of currents in the linear and zero working wires at the input of the load node, measurements were carried out by certified electrical measuring instruments. The analysis of the results obtained for the load node whose power was formed mainly by a lighting system with fluorescent and LED lamps and a system of office electrical receivers (computers, copiers, printers, scanners, etc.) was performed. It can be concluded that a current comparable to the currents of the linear wires of the network flows from the load node with the predominant nonlinear power receivers through the zero-working wire. At the same time, in the zero-working wire of the network, the third harmonic currents prevail over the main frequency currents.

Key words: harmonic currents, non-linear power receiver, non-symmetry, three-phase four-wire network, zero working wire of the network

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1. Introduction

At the end of the 20th century, most of the electrical energy was consumed by linear loads. Since the end of the 90s, due to the sharp and rapid growth of computer technology, the share of non-linear power consumers has sharply increased, for which built-in switching power supply is used. They are non-linear loads whose resistance changes over time. The current consumed by these sources has a pronounced pulse character, that is, in contrast to the sinusoidal current of linear loads [1], it is a periodic non-sinusoidal signal [2, 3].

In a three-phase system, with a symmetrical linear load, there is no current in the neutral wire (or its value will be less than the phase ones) [4]. If the main energy consumption falls on non-linear loads, there are recommendations to double the cross-section of the neutral conductor (relative to the cross-section calculated for the phase conductors) [5]. This is due to the fact that a significant number of current harmonics that are multiples of three will also flow in the neutral wire [6].

The main reasons for current appearance in the zero-working wire of a three-phase four-wire network are the asymmetry of the loads in the phases and presence of nonlinear power receivers [7–11]. When flowing through a zero-working wire, the components of the currents of higher harmonics and asymmetries cause additional losses of voltage and electricity [12]; reduction in the service life of cable lines [13]; increasing the resistance of grounding devices of electrical installations [14]; interference in low-voltage communication lines [15].

The study of the amplitude-phase-frequency characteristics of currents flowing in an electric network with a predominant non-linear load is one of the most urgent tasks, the solution of which will increase the efficiency of electric power transmission and eliminate the negative consequences due to the current flow in a zero-working wire in the network 0.38 kV [16]. In Russia, 0.4 kV is accepted as the nominal voltage for generators and low voltage buses of power transformers, and for networks, the nominal voltage is 0.38 kV. A 5% markup between the specified nominal voltages compensates for the voltage drop in the line during electricity transmission.

Since the spectral composition of currents in real electric networks is influenced by a large number of simultaneously influencing factors (the composition of power receivers in the load node, their connection diagram, switching frequency, etc.), the study of the harmonic composition of currents of the most common typical consumers is of practical interest.

2. Characteristics of the distortion coefficient of the sine curve in accordance with daily changes

The power of the load node under study was formed mainly by a lighting system with fluorescent and LED lamps and a system of office electrical receivers (computers, copiers, printers, scanners, etc.). To study the effect of load changes on the amplitude-phase-frequency characteristics of currents in the linear and zero working wires at the input of the load node, measurements were carried out by certified electrical measuring instruments. The “Resource-UF2M” and “Hioki 3196” devices-controlled currents in linear and zero working (“Hioki 3196”) wires. At the same time, the same devices measured the phase voltages at the input to the load node. The change in the total active power at the input of the load node during the day is shown in Fig. 1.

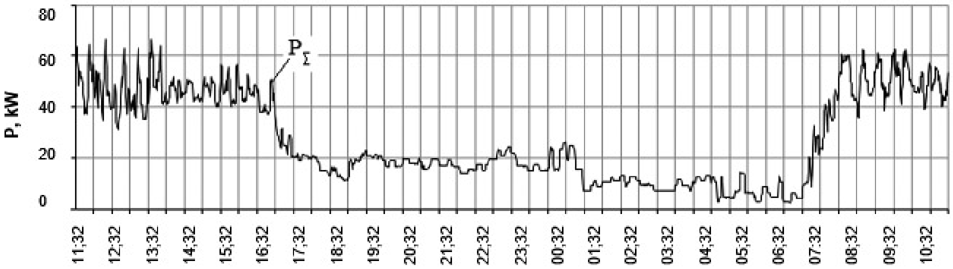


Fig. 1. Schedule of changes in total active power at the input of the load node

The range of changes in the total active power is large – from 5 kW at night and up to 68 kW during the day. The greatest loads were during daylight hours from 7:30 to 17:00 hours. In accordance with the daily load schedule (Fig. 1), it is clearly two-stage, therefore, it is similar for the rest of the working days of the week. The highest currents in the neutral working wire take place during the daytime, therefore this time range was chosen. The minimum value of the total active power, as follows from Fig. 1, was recorded in the morning (from 5:00 to 7:00 hours), and the maximum – in the daytime from 12:00 to 13:32 hours. As can be seen from Fig. 1, the power consumption of the load node occurred according to a two-stage schedule.

Moreover, the change in active capacities during the day is very asymmetric in the network phases (Fig. 2). The active power P_1 of the first phase L_1 during the day turned out to be the smallest most of the time. Separate bursts of the active power P_1 of the phase L_1 were clearly observed in the period from 5:00 to 6:00 hours, when the load was the greatest. Most of the day time, the greatest load fell on the L_3 phase with an active power of P_3. Only in the period from 14:00 to 16:32 hours the active power of P_2 exceeded P_3.

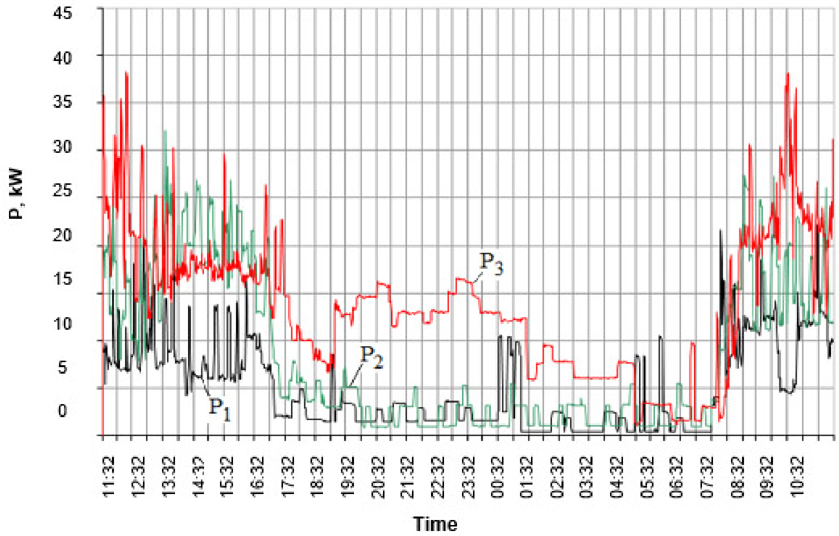


Fig. 2. Schedule of changes in total active power at the input of the load node

Due to the asymmetric load of the phases, the voltage asymmetry coefficients in the zero and reverse sequences of the fundamental frequency were significant (Fig. 3). So, for example, the voltage asymmetry coefficient in the zero sequence of the fundamental frequency (K_{0U}) did not fall during the day, even with a minimum (below 2%) load. During periods of greatest power consumption (from 8:00 to 17:00 hours), the voltage unbalance coefficient in the zero sequence of the fundamental frequency often exceeded 5%. The voltage asymmetry coefficient in the reverse sequence of the fundamental frequency (K_{2U}) during the day had lower values. Moreover, it turned out to be more stable than the coefficient K_{0U}. The range of variation of K_{2U} ranged from 2% to 4%.

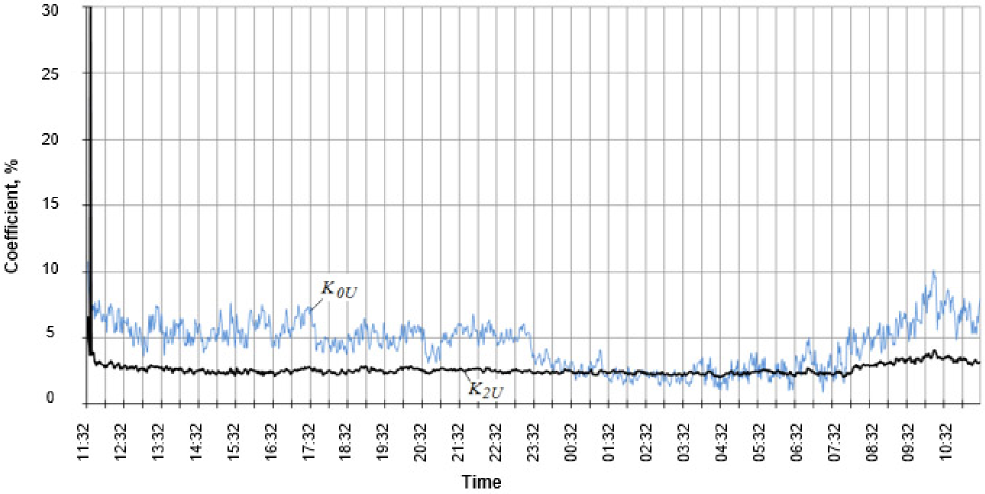


Fig. 3. Diagrams of daily changes in the voltage asymmetry coefficients in the zero and reverse sequence at the input of the load node with the prevailing non-linear power receivers

Fig. 4 shows graphs of daily changes in the distortion coefficients of the sinusoidality of the voltage curves in the phases of the network at the input of the load node 0.38 kV. It should be noted that in none of the phases at the input of the load node the distortion coefficient of the sinusoidality of the voltage curves did not exceed the minimum allowable value – 8%. During periods of maximum load (from 8:00 to 17:00 hours), the distortion coefficient of the sinusoidality of the voltage curve in the first phase K_{U1} was the largest, more than 6% (see Fig. 4). During load shedding, the distortion coefficients of the sinusoidality of the voltage curves in phases became the same (over 2%).

The average amplitude-frequency characteristic of the most significant average daily coefficients of the 3rd, 5th, 7th, 9th and 11th voltage harmonics [17] in the phases of the network 0.38 kV at the input to the load node (Fig. 5) clearly shows that the odd harmonic voltage components prevail over even ones.

Among the odd higher voltage harmonics, the 3rd, 5th, and 9th harmonics had the largest amplitudes. It should be noted that the largest amplitudes of the 3rd and 5th voltage harmonics were recorded in the first phase, and the 9th voltage harmonic was the largest in the second phase

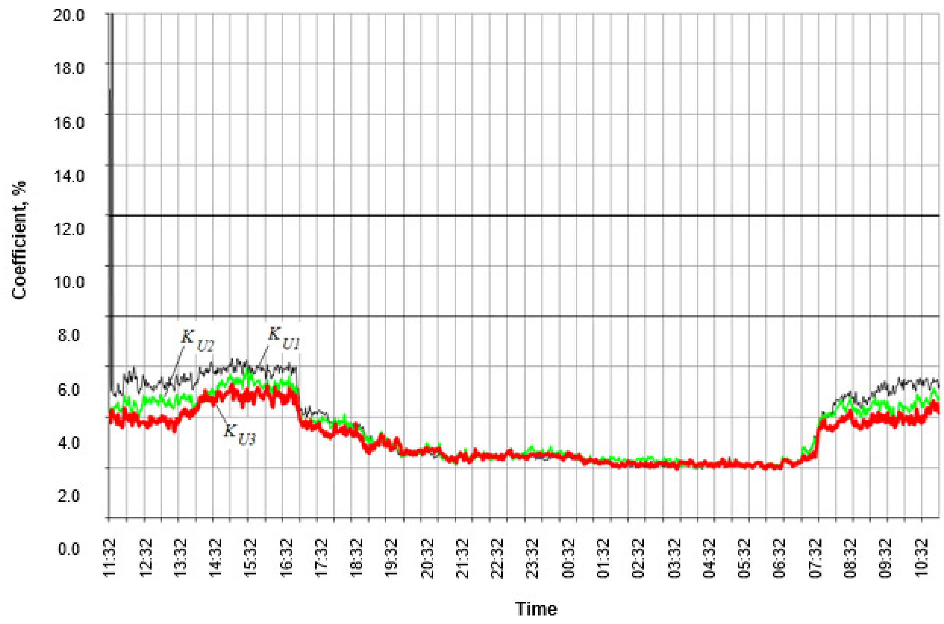


Fig. 4. Diagrams of daily changes in the distortion coefficients of the sinusoidality of the phase voltage curves at the input of the load node with predominant non-linear power receivers

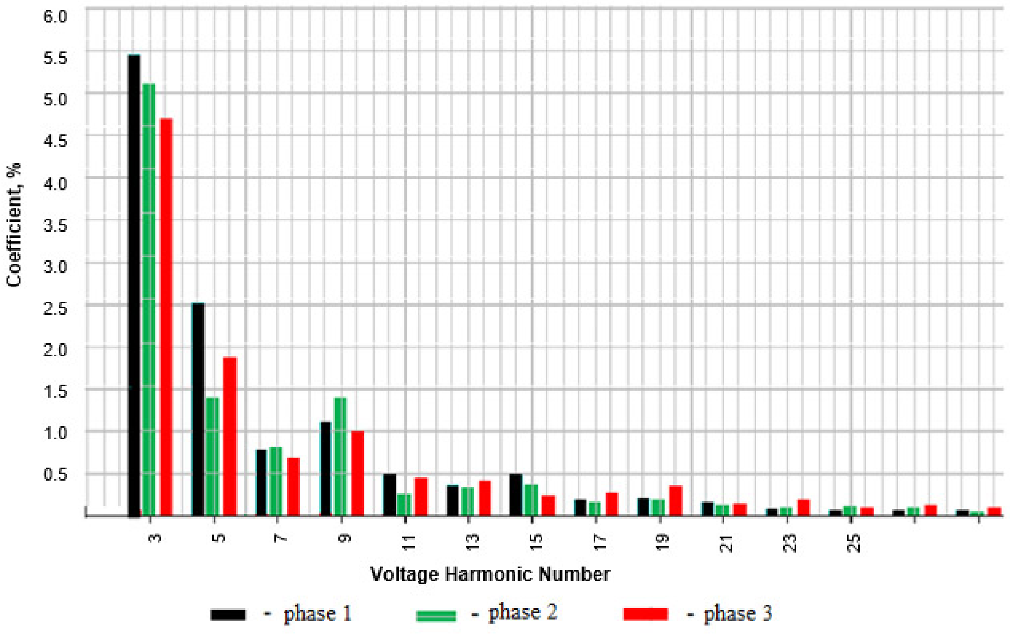
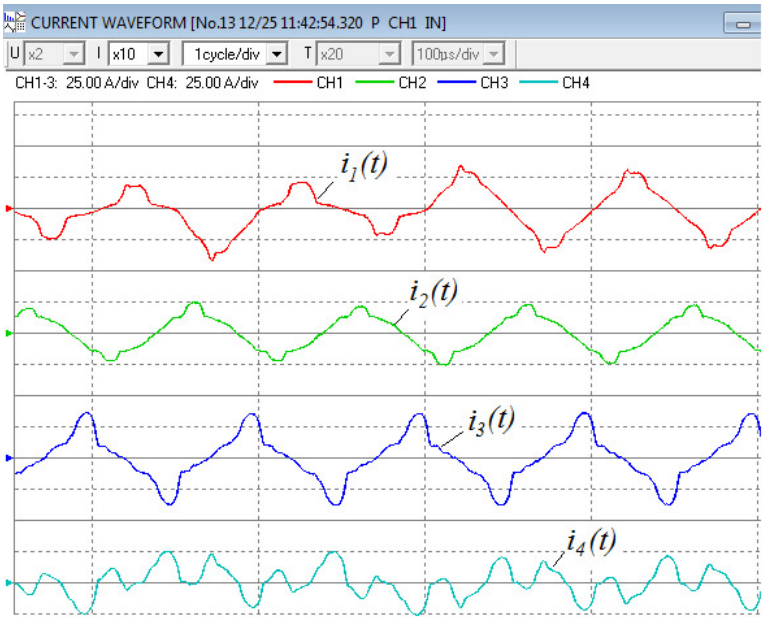


Fig. 5. Frequency response of the most significant daily average coefficients of the n-th harmonic components of the phase voltage at the input of the load node

of the network 0.38 kV (Fig. 5). The coefficients of the 3rd voltage harmonic by phase at the input to the load node varied from 4.7% to 5.5%, the coefficients of the 5th voltage harmonic, respectively, from 1.4% to 2.5%, and the coefficients of the 9th voltage harmonic, respectively, from 1.0% to 1.4% (Fig. 5).

3. Changes in current parameters at various loads of the power receiver

To assess the degree of distortion of currents' sinusoidality during the period of the highest loads, the waveforms of the phase currents and in the zero-working wire at the input of the load node were recorded using the "Hioki 3196" instrument (Fig. 6). The capabilities of the measuring device made it possible to register up to 100 events in the device memory and up to 1000 events on an external memory card for "Hioki 3196". The "Resurs" device allowed to store information in memory for up to 15 days. The recording intervals were 60 seconds. Instrument synchronization frequency is 42.5–69 Hz.



CURRENT WAVEFORM [No.13 12/25 11:42:54.320 P CH1 IN]

U x2 I x10 1cycle/div T x20 100µs/div

CH1-3: 25.00 A/div CH4: 25.00 A/div

Fig. 6. A fragment of the waveforms of the phase currents and the zero-working wire at the input of the load node with the prevailing non-linear power receivers

The current waveforms correspond to the time interval on the daily graph of the change in the total active power at the highest load (from 11:40 to 12:00 hours according to the schedule of Fig. 1). An analysis of the current shape in the zero-working wire $i_4(t)$ on the waveform shows (Fig. 6) that it is not substantially sinusoidal. The waveforms of currents in the linear wires of the load node $i_1(t)$, $i_2(t)$ and $i_3(t)$ are also significantly distorted by higher harmonics.

Using the "Hioki 3196" software package, the amplitudes and phases of the currents were determined for seven significant harmonic components not equal to zero (odd harmonics from the 1st to the 13th). For compact recordings, these transformations are presented in the form of Fig. 7, which also shows mathematical models (expressions) of instantaneous current values at the input to the load node. In Fig. 7, 8, the Fourier expansion is performed up to the 50th harmonic of the current. This allows us to justify the selection of the seven most significant harmonic components of the current by comparison. The sinusoidal distortion coefficients of the curves (see Fig. 7–8) are denoted by THD (Total Harmonic Distortions) and are called the "total current harmonic distortion coefficient". European Standard EN 62040-3 for quality of mains electricity [18] regulates the THDI index.

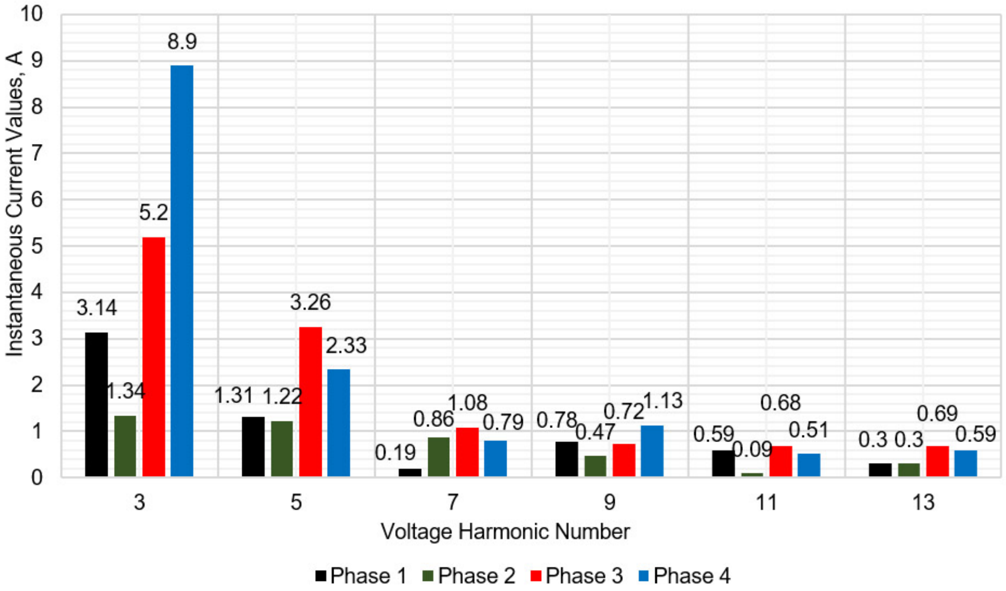


Fig. 7. Diagrams of currents and voltages at a frequency of 150 Hz at the input of a load node with predominant nonlinear power consumers

As can be seen from Fig. 1, the values of the sinusoidality distortion coefficients of the current curves $THDI_1$, $THDI_2$ and $THDI_3$ significantly exceed the similar voltage coefficients (Fig. 5). In the first linear wire L_1 at the input of the load node, the total THDI current distortion factor for the considered time was 23.7%, in the second wire L_2 – 15.98%, in the third wire L_3 – 36.18%, and in the neutral wire – 138.35%, respectively (Fig. 7).

The analysis of the harmonic composition of the current of the zero-working wire $i_4(t)$ is of interest. As can be seen from Fig. 1, in the working (mean square) current I_4, the proportion of the main harmonic of the current is 6.77 A. The proportion of the third harmonic components of the currents flowing in the linear wires of the network 0.38 kV, in the zero-working wire for the considered time point, is 8.9 A, in 5th harmonic current, respectively, 2.33 A, 7th – 0.79 A, 9th – 1.13 A, 11th – 0.51 A and 13th – 0.58 A.

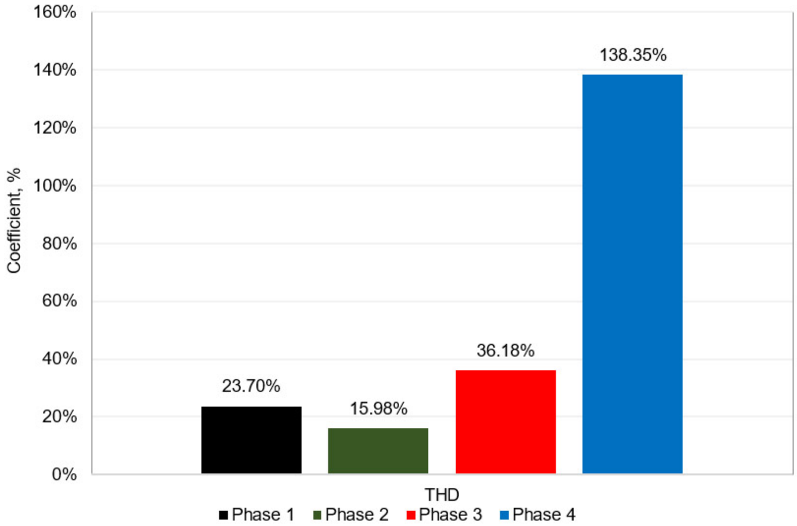


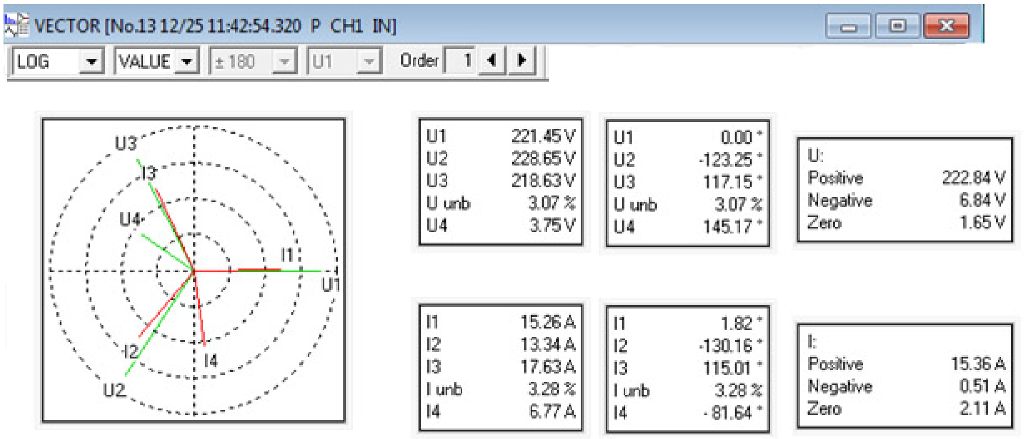
Fig. 8. Diagrams of currents and voltages at a frequency of 150 Hz at the input of a load node with predominant nonlinear power consumers

In this case, the total current load of the zero-working wire for the considered time was equal to 12.48 A. With this load mode, the current values in the linear wires of the network 0.38 kV were as follows: $I_1 = 16.63$ A; $I_2 = 13.54$ A; $I_3 = 18.8$ A. That is, the current load of the zero working wire is commensurate with the load of the linear wires. Obviously, the third and ninth current harmonics make the main contribution to the increase in the current load of the zero-working wire to the values of the currents flowing in the linear wires of the network 0.38 kV (Fig. 8).

Fig. 9, obtained using the "HIOKI 3196" instrument software, shows the logical vector diagrams of currents and voltages at the input of the load node with prevailing nonlinear power receivers at time 11:42 (see Fig. 1). Along with this, the amplitude of the third harmonic of the current $i_4(t)$ is greater than the amplitude of the fundamental harmonic. In addition to the current values of voltage and current, the phase shifts of each value are also indicated here. For the first harmonic (frequency 50 Hz) the components of the direct (Positive), reverse (Negative) and zero (Zero) sequences of voltages and currents are given. With these components, real three-phase voltage and current systems can be balanced to a symmetrical system [19].

Similar characteristics for the considered time and frequency of 150 Hz are presented in Fig. 10.

A distinctive feature of the vector diagrams of voltages and currents of the third harmonic (Fig. 10) is the lack of common mode between the vectors of different phases. Along with the lack of phase matching of vectors, they are also characterized by inequality in magnitude. So, for example, the effective current of the third harmonic in the first phase is 3.14 A, in the second phase, respectively, 1.34 A and in the third phase 5.2 A (see Fig. 1). This is explained by the nature of the formation of these currents in the load node in case of accidental switching on of various power consumers under different voltages.


VECTOR [No.13 12/25 11:42:54.320 P CH1 IN]

U1	221.45 V
U2	228.65 V
U3	218.63 V
U unb	3.07 %
U4	3.75 V

U1	0.00 °
U2	-123.25 °
U3	117.15 °
U unb	3.07 %
U4	145.17 °

U:

Positive	222.84 V
Negative	6.84 V
Zero	1.65 V

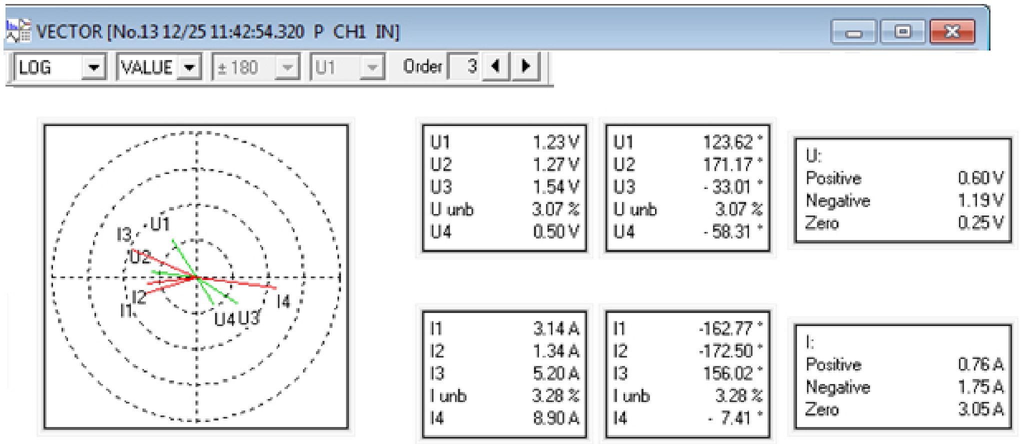
I1	15.26 A
I2	13.34 A
I3	17.63 A
I unb	3.28 %
I4	6.77 A

I1	1.82 °
I2	-130.16 °
I3	115.01 °
I unb	3.28 %
I4	- 81.64 °

I:

Positive	15.36 A
Negative	0.51 A
Zero	2.11 A

Fig. 9. Vector diagrams of currents and voltages at a frequency of 50 Hz at the input of a load node with predominant nonlinear power consumers


VECTOR [No.13 12/25 11:42:54.320 P CH1 IN]

U1	1.23 V
U2	1.27 V
U3	1.54 V
U unb	3.07 %
U4	0.50 V

U1	123.62 °
U2	171.17 °
U3	- 33.01 °
U unb	3.07 %
U4	- 58.31 °

U:

Positive	0.60 V
Negative	1.19 V
Zero	0.25 V

I1	3.14 A
I2	1.34 A
I3	5.20 A
I unb	3.28 %
I4	8.90 A

I1	-162.77 °
I2	-172.50 °
I3	156.02 °
I unb	3.28 %
I4	- 7.41 °

I:

Positive	0.76 A
Negative	1.75 A
Zero	3.05 A

Fig. 10. Vector diagrams of currents and voltages at a frequency of 150 Hz at the input of a load node with predominant nonlinear power consumers

From the vector diagram in Fig. 9 it follows that in order to reduce the current load on the neutral working wire of the network, it is necessary to reduce the zero-sequence current of the fundamental frequency by balancing the load in the electrical network. Vector diagram in Fig. 10 indicates the need for filters to suppress currents with a frequency of 150 Hz.

The results obtained are consistent with studies on the current asymmetry in electrical networks of 0.38 kV, given in papers [4] and [5]. The non-sinusoidal currents and their negative impact on the 0.38 kV network are discussed in papers [6–8]. The presented findings on non-sinusoidality currents do not contradict the abovementioned studies.

4. Conclusions

The analysis of the research results shows that the active use of switching power supplies in electrical appliances leads to an increase in harmonic distortions of voltages and currents in the electrical network. Moreover, the distortion coefficients of the sinusoidality of the voltages have lower values than the distortion coefficients of the sinusoidality of the load currents. In the presence of non-linear power receivers, the current in the zero-working wire of a three-phase four-wire network is comparable with the currents in linear wires. So, in the maximum load mode, with the current value of the zero working wire current 12.48 A, the currents of the linear wires were I_1 = 16.63 A, I_2 = 13.54 A and I_3 = 18.8 A, respectively.

Based on the obtained results of the study, it can be argued that the currents of the third harmonic component, which dominate in the neutral working wire of the network 0.38 kV, are not in-phase in the linear wires. The results obtained are of great practical importance when designing technical means that provide current unloading of the zero-working wire of the network 0.38 kV and, ultimately, reduce energy losses during transmission.

Appendix

kV	kilovolt,
kW	kilowatt,
A	ampere,
P	active power,
K_{0U}	voltage asymmetry coefficient in the zero sequence of the fundamental frequency,
K_{2U}	voltage asymmetry coefficient in the reverse sequence of the fundamental frequency,
K_{U1}	voltage curve in the first phase,
K_{U2}	voltage curve in the second phase,
Hz	hertz,
$i_4(t)$	AC sinusoidal current,
L	linear wire (phase),
I	current load,
U	voltage,
THD	(Total Harmonic Distortion) is a measurement that tells you how much of the distortion of a voltage or current is due to harmonics in the signal,
HDI	harmonic distortion of current,
HDU	harmonic distortion of voltage.

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