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IMPACT OF ELECTRIC ENERGY QUALITY ON FIRE SAFETY OF TRANSFORMERS

Abstract

The use of non-linear devices causes unfavourable changes in the operation of the power system. First of all, they are a source of higher harmonics in network waveforms, which tend to increase the eddy currents. Their effect consists in raising the temperature of transformer cores. This, in turn, translates into their failure rate and fire safety, including reducing the actual value of rated power. The article describes the results of experimental studies carried out on a large scale. An analysis was performed of the quality of electric power depending on the type of network load. The results have shown that the increase in the use of non-linear receivers such as LED lighting, electronic chargers, inverters, etc. may have a tangible impact on the fire hazard of distribution transformers. Examples of calculations have been presented, which prove the necessity of taking into account the influence of higher harmonics on the reduction of the real rated power of power transformers.

Keywords: power quality, transformer, fire safety

BADANIE WPŁYWU JAKOŚCI ENERGII ELEKTRYCZNEJ NA BEZPIECZEŃSTWO POŻAROWE TRANSFORMATORÓW ENERGETYCZNYCH

Abstrakt

Użytkowanie urządzeń o charakterze nieliniowym wprowadza niekorzystne zmiany w funkcjonowaniu systemu elektroenergetycznego. Przede wszystkim są one źródłem wyższych harmonicznych w przebiegach sieciowych, co wpływa na zwiększenie prądów wirowych. Ich oddziaływanie sprowadza się do podnoszenia temperatury rdzeni transformatorów. To z kolei przekłada się na ich awaryjność i bezpieczeństwo pożarowe, w tym na obniżenie rzeczywistej wartości mocy znamionowej. Artykuł opisuje wyniki badań doświadczalnych przeprowadzonych w dużej skali.

Analizie poddano jakość energii elektrycznej w zależności od rodzaju obciążenia sieci. Wyniki pozwalają stwierdzić, że wzrost wykorzystania nieliniowych odbiorników takich jak: oświetlenie LED, ładowarki elektroniczne, przetwornice częstotliwości itp. może realnie wpływać na zagrożenie pożarem transformatorów rozdzielczych. Przedstawiono przykładowe obliczenia, które dowodzą konieczności uwzględnienia wpływu wyższych harmonicznych na obniżenie rzeczywistej mocy znamionowej transformatorów energetycznych.

Słowa kluczowe: jakość energii elektrycznej, transformator, bezpieczeństwo pożarowe

1. Introduction

1.1. Electric power quality

The quality of electricity supplied to consumers has been strictly defined in relevant Polish regulations. The basic legal act normalising the requirements in this respect is the *Ordinance of the Minister of Economy on the detailed rules for the operation of the power system of May 4, 2007* [1]. Chapter 10 of the abovementioned document contains the parameters that must be met by a smoothly functioning network. The requirements were listed below.

- For entities included in consumer groups III–V[1]:
  - o the average frequency value measured for 10 seconds should be within the range: 50 Hz ±1% over 95.5% of the week,
  - o 50 Hz ±4% over 100% of the week;
- each weekly 95% of the set of 10-minute average value of the effective supply voltage should not exceed ±10% of the rated voltage;
- long-term transfer coefficient of flicker P_{lt} resulting from supply voltage fluctuations 95% of the time each week should not exceed 1%;
- each weekly 95% of the 10-minute mean effective value set:
  - o with a symmetrical sequence component of the supply voltage should be within the range from 0% to 2% of the positive sequence value,
  - o for each harmonic of the supply voltage it should be less than or equal to the values specified in Table 1;
  - o THD of higher harmonic distortion of the supply voltage up to the 40th order should not exceed 8% [1].

[1] group III: connected directly to a network of rated voltage > 1 kV, but lower than 110 kV; group IV: connected to a network of rated voltage not higher 1 kV and a connection rated power > 40 kW or with main overcurrent protection higher than 63 A; group V: connected to the network of rated voltage not higher than 1 kV, connection rated power up to 40 kW and main overcurrent protection up to 63 A.

Table 1. Requirements for the quality of electricity in the field of higher harmonics according to Polish regulations

Odd harmonics				Even harmonics	
not being a multiple of 3		being a multiple of 3			
harmonic (h)	relative voltage value in percentage of the fundamental frequency (u_h)	harmonic (h)	relative voltage value in percentage of the fundamental frequency (u_h)	harmonic (h)	relative voltage value in percentage of the fundamental frequency (u_h)
5	6%	3	5%	2	2%
7	5%	9	1.5%	4	1%
11	3.5%	15	0.5%	> 4	0.5%
13	3%	> 15	0.5%		
17	2%				
19	1.5%				
23	1.5%				
25	1.5%				

Source: own study

As regards the above-mentioned parameters, the research covered: the average frequency value, the average value of the effective supply voltage and the THD of higher harmonic distortion. However, in the first place an analysis of the amplitude of higher harmonics was performed on the basis of the recorded voltage waveforms.

Measurements were carried out in actual working conditions. The switchgear of the tested installation is in the Main School of Fire Service in Warsaw, Poland. The grid covers cadet officers' accommodation building and provides electricity distribution for almost 90 people. The basic receivers powered from the switchboard are laptops, phone chargers, kettles, washing machines and refrigerators, as well as lighting equipment.

The typical elements causing the formation of higher harmonics are as follows:

- transformers – they contain ferromagnetic elements in the form of a core, causing deformations. This is due to the nonlinear magnetization characteristics of the core;
- frequency converters – they contain semiconductor elements such as thyristors, which are non-linear (semiconductor) elements and at the same time a source of deformation;
- LED lighting, due to the use of non-linear characteristics of the diodes;
- a device that uses electric arc – the characteristics of the electric arc are also non-linear. Devices such as arc furnaces or welding machines have an impact on the distortion of current and voltage waveforms in the network [2].

The quality of electricity decreases with increasing non-sinusoidal currents that distort the sinusoidal supply voltage. The reason for this phenomenon is the use of devices that contain non-linear elements. The current waveform distortions can be broken down with the use of Fourier transform into a sinusoidal current with a fundamental frequency of 50 Hz and following harmonic components, the frequencies of which are usually a multiple of the fundamental frequency [3].

1.2. Influence of the quality of electricity on the operation of transformers

Transformers are one of the most important devices operating in the power system. Their primary task is to convert electric energy (voltages and currents) from one circuit, the so-called primary circuit, to the second one, a secondary circuit, while maintaining a constant frequency value [4]. The entire transformation process takes place thanks to the use of the magnetic coupling of both circuits [5].

Due to their role and application, transformers are divided into:

- Unit transformer – cooperating with generators, they are used to increase the voltage to the rated voltage of the transmission grid;
- Power transformer – connecting two high voltage grids or transmission grids with distribution grids;
- Distribution transformer – used to lower the voltage, e.g. from 15 kV to 0.4 kV [6].

The electricity transmission diagram is shown in Figure 1.

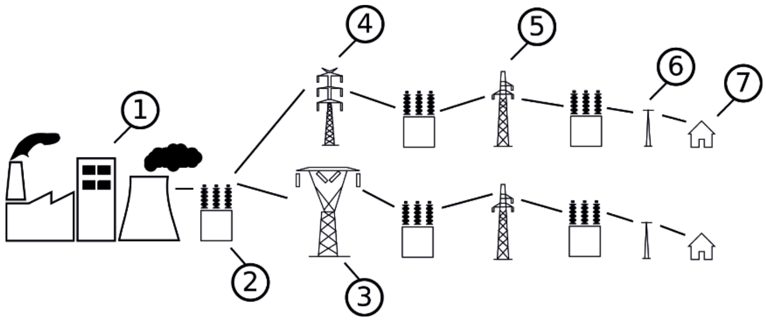

Fig. 1. Diagram of the transmission and distribution grid: 1) power plant; 2) block transformer; 3) extra-high voltage overhead transmission line; 4) high voltage overhead transmission line; 5) medium voltage overhead distribution line; 6) low voltage distribution overhead line; 7) final recipient

Source: [7]

The voltage of the produced electricity is primarily raised in the stations located on the premises of the power plant from the medium voltage value to the high or extra high voltage values of 220 or 400 kV. This procedure is aimed at reducing heat losses (according to Joule-Lenz law) caused by the transmission of electricity over long distances. The higher the voltage, the lower the current, and thus the less heat is dissipated by the wires. Then the electric energy is directed to transmission lines, which are used to deliver it to the extra high voltage and high voltage transformer stations. The voltage is changed by means of power transformers.

Another element of the energy transmission system is the 110 kV high voltage line, from which the energy goes to another power transformer, this time converting high voltage to medium voltage. From there, the electricity goes to medium voltage distribution grid with a voltage of up to 30 kV. The next element in the current path is a distribution transformer that converts medium voltage to low voltage. Electric energy (voltage 400/230 V) goes to the recipient's power connection. Through the internal power line, the energy flows through the meter and goes to the switchboard, where is redirected to particular circuit.

Currently, there is an increasing number of electronic devices working in the power system. This group includes, among others, rectifiers, choppers, inverters and frequency converters. Their presence has a decisive influence on the formation of higher harmonics, which are disturbances in voltages and currents.

The deformation of the currents in the transformer windings increases the power losses, and hence its temperature. The presence of non-linear receivers causes the current waveform to become non-sinusoidal. It is the source of increased share of higher harmonics.

It is assumed that the power of losses Δp_{def} in higher harmonics depends on the square of the effective value of the current and the square of the frequency [8]. It was expressed by the equation (1).

$$\Delta p_{\mathrm{def}} = a_1 I_1^2 f_1^2 + a_2 I_2^2 f_2^2 + \ldots + a_n I_n^2 f_n^2 \tag{1}$$

where: I_1, I_2, I_n – rms value of harmonic currents, a_1, a_2, a_n – coefficients, f_1, f_2, f_n – harmonic frequencies.

The increase in additional losses (Δp_{def}) in comparison with the losses for the sinusoidal current (Δp_{sin}) determined by the formula (2) was determined by the coefficient K, which is described by the formula (3).

$$\Delta p_{\mathrm{def}} = a I^2 f_1^2 \tag{2}$$

$$\mathrm{K} = \frac{\Delta p_{\mathrm{d\,def}}}{\Delta p_{\mathrm{d\,sin}}} = \frac{a_1 I_1^2 f_1^2 + a_2 I_2^2 f_2^2 + \ldots + a_n I_n^2 f_n^2}{a_1 I^2 f_1^2} \tag{3}$$

Assuming that the coefficients are equal, i.e. $a_1 = a_2 = a_n = a$, the above formula can be written in the following form (4):

$$K = \frac{\sum_{i=1}^{n} I_i^2 f_i^2}{I^2 f_1^2} = \sum_{i=1}^{n} \left(\frac{I_i}{I}\right)^2 \left(\frac{f_i}{f_1}\right)^2 \tag{4}$$

where: $\frac{I_1}{I} = h_i$ – the share of i-th current harmonic, $\frac{f_i}{f_1} = n$ – i-th current harmonic, which ultimately gives the following relationship (5):

$$K = \sum_{i=1}^{n} \left(h_i\right)^2 (n)^2 \tag{5}$$

The knowledge of the K coefficient of the increase in additional losses in the transformer makes it possible to determine allowable power at which the maximum allowable temperature of the transformer would not be exceeded.

By additionally introducing the K_s coefficient described by the formula (6), it is possible to calculate how the rated power of the transformer has changed [8]:

$$K_S = \frac{S_{\text{n sin}}}{S_{\text{n def}}} = \sqrt{\frac{1 + \delta p_{\text{d sin}}}{1 + K\delta p_{\text{d sin}}}} \tag{6}$$

where: $S_{\text{n, sin}}$ – rated power of the transformer at sinusoidal load, $S_{\text{n, def}}$ – maximum allowable power at non-linear conditions (deformed current).

The most important conclusion of the quoted study is the fact that the significant content of higher harmonics would reduce the allowable power of the transformer in relation to the designed rated power. This means that the change of the nature of the load itself, without exceeding the rated currents, may lead to overheating of the transformer and, as a result, to its destruction / fire.

1.3. Fire hazard related to transformers

Eddy currents are one of the types of losses in conductive materials that are within the range of the time-varying magnetic field. They cause the release of heat, which raises the temperature, among others, of the transformer core. The loss P per mass unit for the transformer core is determined according to the equation (7) [9]:

$$P = \frac{\pi^2 B_p^2 d^2 f^2}{6\rho D} \tag{7}$$

where: P – power loss by the unit of weight, W/kg; B_p – peak magnetic field, T; d – thickness of the metal sheet (core), m; f – frequency, Hz; ρ – material resistivity, Ωm; D – material density, kg/m^3.

At the same time, the value of the magnetic induction B produced by a circular conductor (coil) depends on the value of the electric current that produces it:

$$B = \frac{\mu I N}{l} \tag{8}$$

where: μ – magnetic susceptibility, H/m; I – coil current, A; N – number of coil turns, l – coil length, m.

This suggests that the losses increase exponentially for the successive harmonics of the current. The greater the share of successive harmonics, the greater the phenomenon. It follows that the greater the deformation of the waveforms recorded in the network, the greater the share of losses on eddy currents in the cores of supply transformers. In fact, it depends on several factors, but it is possible to rule out the participation of harmonics in the excessive heating of transformers (compared to circuits loaded only with linear devices).

2. Method

2.1. Measuring device

A SONEL power quality analyser, model PQM-711, was used to perform the measurements. The device has five voltage measurement inputs. They are marked with symbols L1, L2, L3, N and PE. The voltage measurement range is 1000 V RMS.

The measurement of the current intensity is carried out by means of four current inputs to which the measuring clamp is connected. In the tests, clamps with the C-4 (A) symbol were used, which allow the measurement of currents up to 1000 A AC.

Data obtained from the device is transferred to the computer via USB port, Wi-Fi radio transmission (communication channel used in the described tests) or GSM. The analyser is powered by mains voltage in the range 100–690 V AC or 140–690 V DC. In the event of a power failure, the device uses a built-in battery. Should the battery become depleted, the meter stops the operation and an emergency shutdown takes place. After restoring power, the analyser resumes recording (if this was previously done) [10].

The measuring device has a calibration certificate and meets the requirements of class A as defined in the standard [11].

2.2. Measurements

2.2.1. General information

The research consisted in recording voltage and current waveforms, along with an automatic analysis of the quality of electricity by determining the values of higher harmonics. The analysed object was the cadet officers' accommodation area of the Main School of Fire Service. The area is located on the first floor of the building, and its electrical installation is powered from a dedicated electrical switchboard.

Measurements were carried out in the following operating states of the electrical installation, marked with letters in order to facilitate an analysis of the obtained empirical data:

A. total shutdown of all devices in the entire area of the accommodation. The exceptions were devices powered by electricity at all times, i.e. WiFi routers, emergency evacuation lighting devices. It can be considered that these measurements provide information on the distortions in the voltage waveforms, or the background for the remaining measurements.
B. Switching on only the lighting devices.
C. Simultaneous commissioning of lighting devices and electronic chargers for mobile devices (mobile phones and laptops).
D. Normal use of the installation (lighting devices, household appliances, electronic chargers for mobile devices – in any configuration chosen by the users).

2.2.2. Measuring circuit and recorded parameters

During the tests, the measuring system shown in Figure 2 was used.

The following parameters were recorded:

- RMS phase and phase-to-phase voltages – up to 1000 V referred to ground (peak voltages up to ±1500 V);
- transient voltages (overvoltages) within the range up to ±8 kV;
- RMS currents: up to 3000 A (peak currents up to ±10 kA) using flexible probes (F-3(A));
- Crest Factors for current and voltage;
- mains frequency within the range of 40–70 Hz;
- active, reactive and apparent power and energy, distortion power;
- harmonics of voltages and currents (up to 50th);
- Total Harmonic Distortion THD_F and THD_R for current and voltage;
- Total Demand Distortion for currents (TDD);
- K-Factor (loss factor in transformers caused by higher harmonics);
- active and reactive powers of harmonics;
- the angles between voltage and current harmonics;

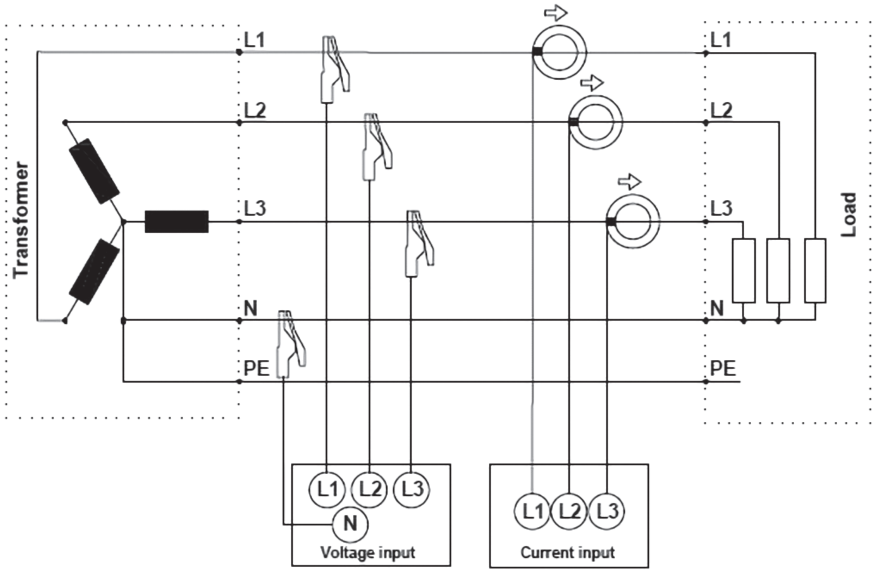

Fig. 2. Diagram of the measuring system
Source: own study

- Power Factor, cosφ (DPF), 4-quadrant tangent;
- unbalance factors and symmetrical components for three-phase mains;
- flicker severity PST and PLT;
- interharmonics of voltages and currents (up to 50th);
- Total Interharmonic Distortion TIDF and TIDR for current and voltage;
- mains signalling voltage in the frequency band of 5–3000 Hz;
- Rapid Voltage Changes (RVC).

Data were acquired in real time in the device's internal memory. Then the data were copied to a computer for analysis in the SONEL ANALIZA 4 software [12].

2.3. Characteristics of the electrical installation and experiment phases

2.3.1. Installation

The tested electrical installation was designed and built in accordance with the current electrical standards. The main means of protection are located in the switchgear in the staircase. Additionally, the circuits in individual rooms are protected by separate switchboards. The most important components have been listed below.

1. Main protection: 3-pole power switch (I_n = 125 A).
2. Overvoltage protection B+C (I_{imp} = 8 kA , I_n = 15 kA , U_p = *1.5* kV , I_{max} = 60 kA with circuit breakers (three C32 breakers).

3. Fusible protection for groups of circuits (I_n = 25 A).
4. Protection of particular circuits:
   a. Corridor
      i. RCD 40 A / 30 mA for circuits in corridors.
      ii. Three B10 circuit breakers for circuits in two parts of the corridors and for emergency evacuation lighting.
      iii. B16 circuit breaker for electric socket in corridors.
   b. Bathrooms (3) and living rooms (24), commanders' room, warehouse:
      i. RCDs 25 A / 30 mA
      ii. B10 circuit breakers for lighting circuits (one circuit per room) and B16 for plug-in sockets (four circuits per room).

The accommodation area is permanently inhabited by 89 cadet officers. During working hours, the company commander and deputy commander are also present in the area.

Specific characteristics of the receivers used during the research are presented in the following sections describing the subsequent phases of the experiment.

2.3.2. Idle – devices disconnected (stage A)

During stage (A) of the test, all users were asked to disconnect all devices from the power grid. Nevertheless, there were circuits in the tested installation, the disconnection of which was not possible without significant interference, in particular the emergency evacuation lighting system. The parameters of these devices are summarized in Table 2.

Table 2. List of the crucial parameters of the emergency lighting equipment connected to electrical grid

Emergency lighting of:	Voltage U_{in}	Power P_n	Number	$\sum P_n$	Battery voltage U_{bat}	Battery capacity Q_{bat}
	V	*W*	-	*W*	*V*	*Ah*
Escape routes	230	3	5	15	3	3
Open area	230	2.8	2	5.6	3.6	0.6
			TOTAL:	**20.6**		

Source: own study

The table includes, inter alia, rated power of devices. During the tests, the devices were able to off-take the energy needed to charge the internal batteries from the mains. Measurements were performed to define a baseline for further experiments.

2.3.1. Lightning devices connected (stage B)

In stage (B) of the experiment, all the lighting devices listed in Table 3 were put into operation in the tested facility.

Table 3. List of crucial parameters of the lighting devices connected to the power grid

Type of lighting device	Voltage U_{in}	Nominal current I_{in}	Nominal power P_n	Number	$\sum P_n$
	V	*A*	*W*	-	*W*
A (rooms)	230	0.18	38	53	2 014
B (corridors)	230	0.18	38	11	418
			TOTAL:	**64**	**2 432**

Source: own study

All the above-mentioned devices use LED and were manufactured by Philips (type: Leinaire RC065B), equipped with an electronic PSU (source of higher harmonics) with a minimum power factor of 0.9, which means that the rated light output is approx. 34 W.

2.3.2. Electronic chargers connected (stage C)

In the next stage (C) of the experiment, the lighting devices were turned off. Electronic devices are connected to the network, in particular computers (key parameters are presented in Table 4) as well as electronic chargers for mobile phones (Table 5).

Table 4. List of crucial parameters of computers connected to the power grid during the experiment

Laptop no.	Nominal input voltage U_{in}	Nominal current I_{in}	Nominal output voltage U_{out}	Nominal output current I_{out}	Nominal power P_n
	V	*A*	*V*	*A*	*W*
1	100–240	3	19.5	10.3	200
2	100–240	1.8	20	3.25	65
3	100–240	1.5	20	4.5	90
4	100–240	2.5	20	8.5	170
5	100–240	3.5	20	11.5	230

tab. 4. cont.

Laptop no.	Nominal input voltage U_{in}	Nominal current I_{in}	Nominal output voltage U_{out}	Nominal output current I_{out}	Nominal power P_n
6	100–240	1.8	20	6.75	135
7	100–240	1.8	19.5	6.9	135
8	100–240	1.7	18.5	3.5	65
9	100–240	2.5	19	7.1	135
10	100–230	1.5	20	3.25	65
11	100–240	1.8	19.5	6.9	135
12	100–240	2.5	19.5	9.23	180
13	100–240	1.8	20	6.75	135
14	100–240	2.5	19.5	9.23	180
15	100–240	1.5	20	3.25	65
16	100–240	1.2	19	2.37	45
17	100–240	2.7	19.5	7.7	150
18	100–240	1.8	20	3.25	65
19	100–240	3.5	20	11.5	230
20	100–240	1.9	19	7.1	135
				TOTAL:	**2 610**

Source: own study

The parameters provided by the manufacturer are ambiguous. The rated output current applies to the lowest rated voltage value, hence the determination of the apparent power S_n for the rated network voltage in Poland is not possible without detailed tests. In addition, the instantaneous value of power consumed from the grid is time-varying and depends, among others, on the nature of the computer's operation (3D modeling vs. working with a text editor) or the current battery charge status. In this situation, the power dissipated in the DC circuit may be an indication of the nature of the devices listed in Table 4, but it should be remembered that the actual load on the electrical network will always be greater (the efficiency η of computer power supplies must be taken into account).

All of the above power supplies have electronic components, which makes them non-linear load, influencing the content of higher harmonics in the tested circuit.

Table 5. List of the crucial parameters of phone chargers connected to electrical grid during the experiment

Charger no.	**Nominal input voltage U_{in}**	**Nominal current I_{in}**	**Nominal output voltage U_{out}**	**Nominal output current I_{out}**	**Nominal power P_n**
1	*V*	*A*	*V*	*A*	*W*
2	100–240	0.5	5	2	10
3	100–240	0.7	11	3	33
4	100–240	0.35	5	2	10
5	100–240	0.5	12	1.5	18
6	100–240	0.5	9	2	18
6	100–240	0.5	9	1.67	15
7	100–240	0.5	9	2.22	20
8	100–240	1.2	11	3	33
9	100–240	1.8	10	6.5	65
10	100–240	0.7	11	3	33
11	100–240	0.7	11	3	33
12	100–240	0.3	5	2.4	12
13	100–240	0.15	5	1	5
14	100–240	0.5	9	2	18
15	100–240	0.5	9	1.67	15
16	100–240	0.6	12	1.5	18
17	100–240	0.7	3	11	33
18	100–240	0.5	9	2	18
19	100–240	0.5	9	1.67	15
				TOTAL:	**422**

Source: own study

Also in the case of phone chargers it is impossible to accurately determine the instantaneous power. The total network load with connected chargers is the peak value, which does not take into account the efficiency η of the devices (analogous to the data presented for computer devices).

2.3.3. Normal operation (stage D)

In the last stage (D) of the research, the operating parameters of the installation under normal operating conditions, i.e. with the nature of the load depending on the current needs of the users, were registered. In addition to the equipment indicated above, household appliances (refrigerators and electric kettles) with the parameters shown in Table 6 were connected to the network.

Table 6. List of the crucial parameters of the household appliances connected to electrical grid during the experiment

Type of appliance	U_{in} V	P_n W
Electric kettle 1	220–240	2200
Electric kettle 2	220–240	2025
Electric kettle 3	220–240	1800
Electric kettle 4	230	700
Electric kettle 5	220–240	2200
Electric kettle 6	220–240	2025
Refrigerator 1	220–240	2200
Refrigerator 2	220–240	2025
Refrigerator 3	220–240	1800
	SUM:	10 950

Source: own study

3. Results

3.1. Idle (stage A)

During stage (A) of the research, only the devices specified above were in operation. The quality of electricity was found to have minor distortions, which is visible for the first three odd harmonics of the fundamental frequency (Fig. 3). Regulatory limit values have not been exceeded. The recorded voltage waveforms are shown in Fig. 4. In order to achieve consistency, the figure captions have been marked with the wording 'idle*', where the asterisk (*) refers to its actual state (minor load).

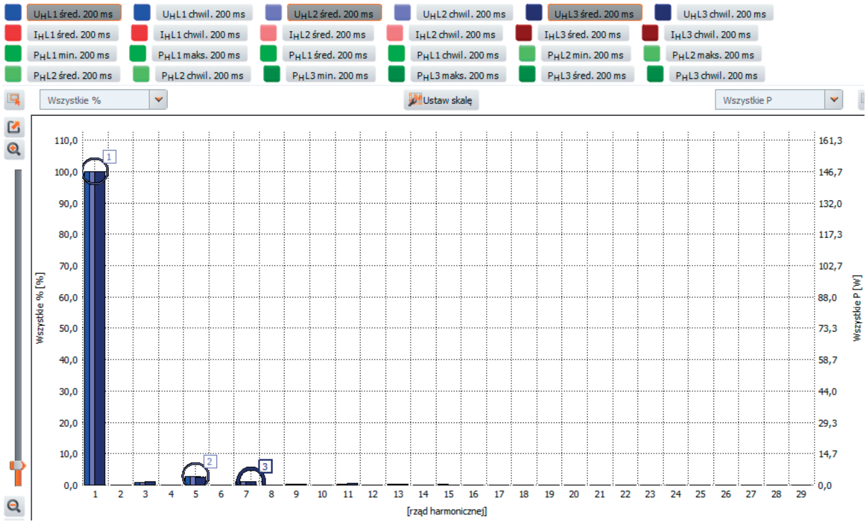

Fig. 3. Voltage harmonics recorded for electrical installation at idle*

Source: own study

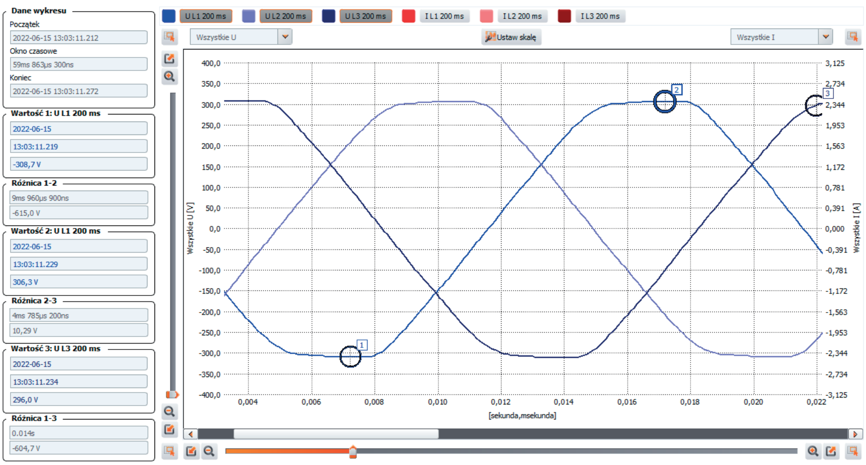

Fig. 4. Voltage waveforms recorded for electrical installation at idle*

Source: own study

The waveforms of the currents received by the load are distorted (Fig. 5), which results from their nature (as described earlier), but due to the low current consumption (peak values not exceeding 0.4 A, 2.3 A, 2 A respectively for particular phases) they do not affect the voltage in the tested electrical installation.

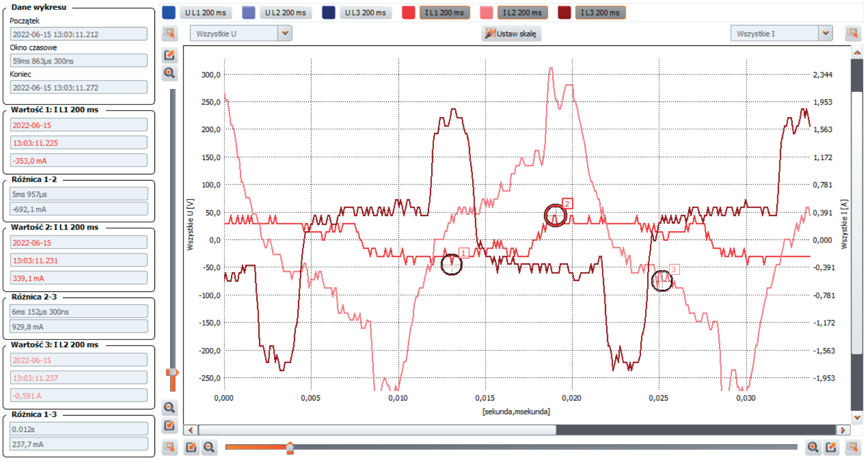

Fig. 5. Current waveforms recorded for electrical installation at idle*

Source: own study

The result of waveform decomposition into harmonic components is shown in Figure 6. The greatest deformations were recorded for the third phase. For the third, fifth and seventh harmonics, they are respectively: 65%, 41%, and 20% of the fundamental harmonic amplitude.

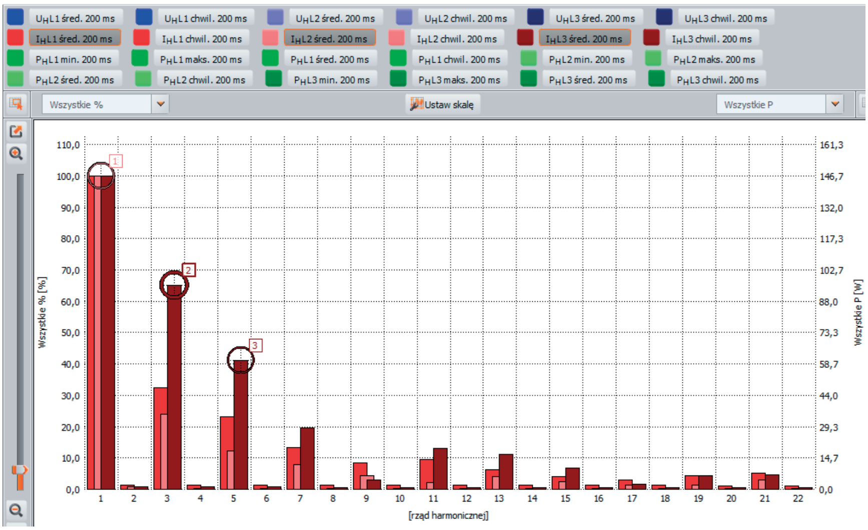

Fig. 6. Current harmonics recorded for electrical installation at idle*

Source: own study

3.2. Lighting devices (stage B)

During stage (B) of the research, all lighting devices were turned on. The quality of electric energy was found to have minor distortions, which are visible for the first three odd harmonics of the fundamental frequency (Fig. 7). Regulatory limit values have not been exceeded.

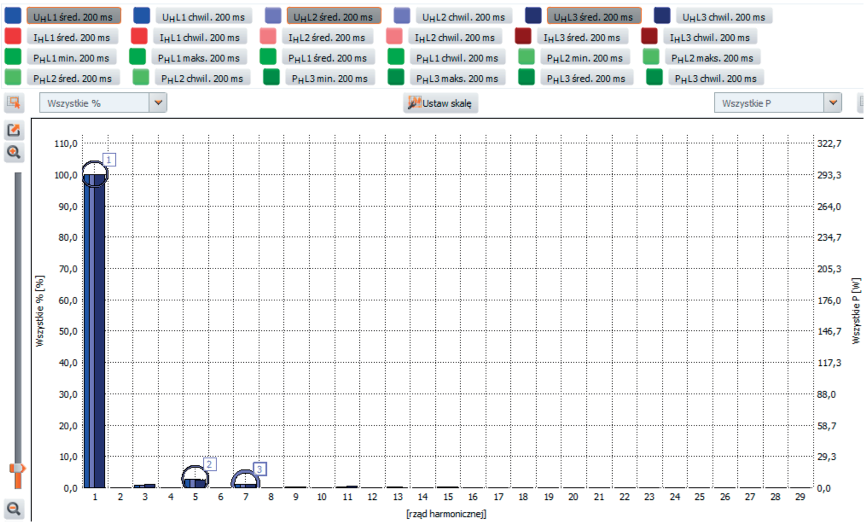

Fig. 7. Voltage harmonics recorded for electrical installation after connection of lighting devices

Source: own study

Distortions of current waveforms typical for LED lighting devices were recorded. Sample waveforms are shown in Figure 8.

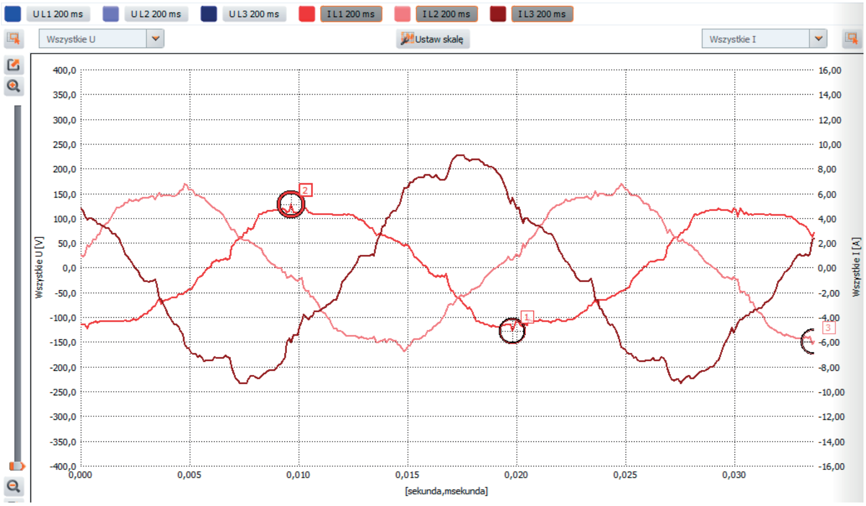

Fig. 8. Current waveforms recorded for electrical installation after connection of lighting devices

Source: own study

The decomposition into higher harmonics (Fig. 9) shows similar distortions of particular phases, which is in line with the expectations resulting from the characteristics of the tested installation. For harmonics 3, 5 and 7 they are maximum (respectively): 11%, 7.5%, 6.5%.

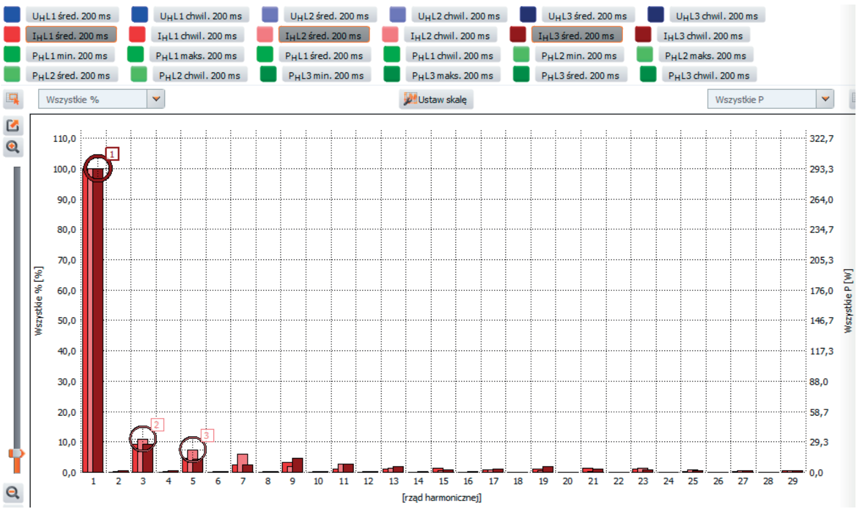

Fig. 9. Current harmonics recorded for electrical installation after connection of lighting devices

Source: own study

3.3. Electronic chargers (stage C)

During stage (C) of the research, all mobile devices (electronic chargers) were turned on. The quality of electricity was found to have minor distortions, which is visible for the first three odd harmonics of the fundamental frequency (Fig. 10). Regulatory limit values have not been exceeded.

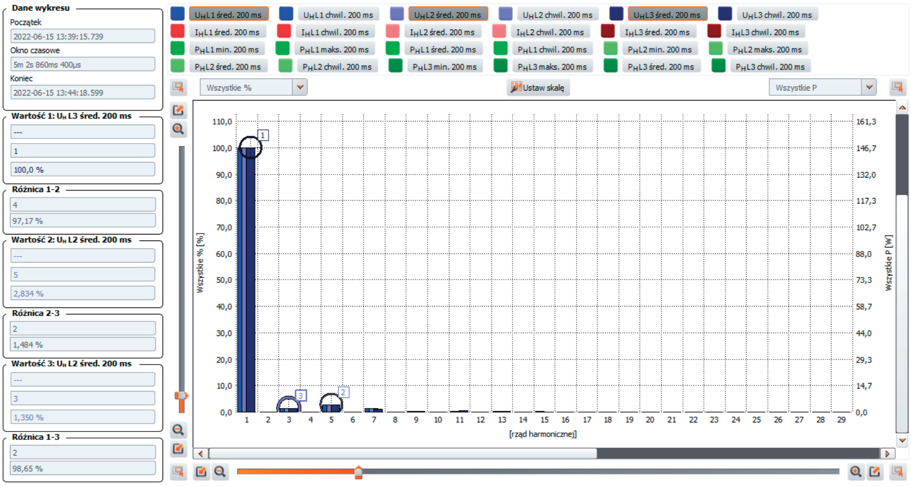

Fig. 10. Voltage harmonics recorded for electrical installation after connection of electronic chargers

Source: own study

Significant distortions of the current waveforms were recorded (Fig. 11). For phase 1, the highest harmonic values were achieved for the 3rd, 5th and 7th harmonics, respectively: 58%, 36% and 23% of the fundamental harmonic amplitude.

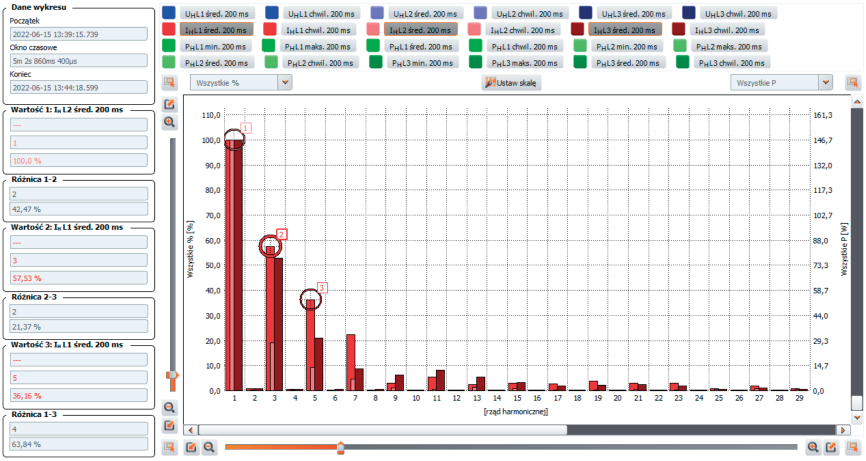

Fig. 11. Current harmonics recorded for electrical installation after connection of electronic chargers

Source: own study

3.4. Normal operation (stage D)

During the research stage (D), the installation was used according to users' needs. The quality of electric energy was found to have minor distortions of voltage waveforms, which is visible for the first three odd harmonics of the fundamental frequency (Fig. 12). Regulatory limit values have not been exceeded.

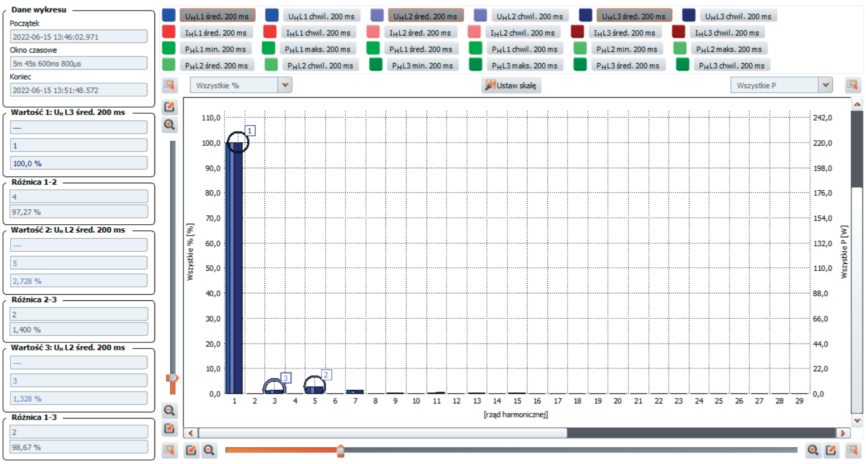

Fig. 12. Harmonics of voltage waveforms recorded at normal operation of the electrical installation

Source: own study

Some distortions of the current waveforms were recorded, the most visible for phase 3 (Fig. 13). For harmonics 3, 5 and 7, the following values were obtained: 20%, 9% and 4%, respectively (Fig. 14).

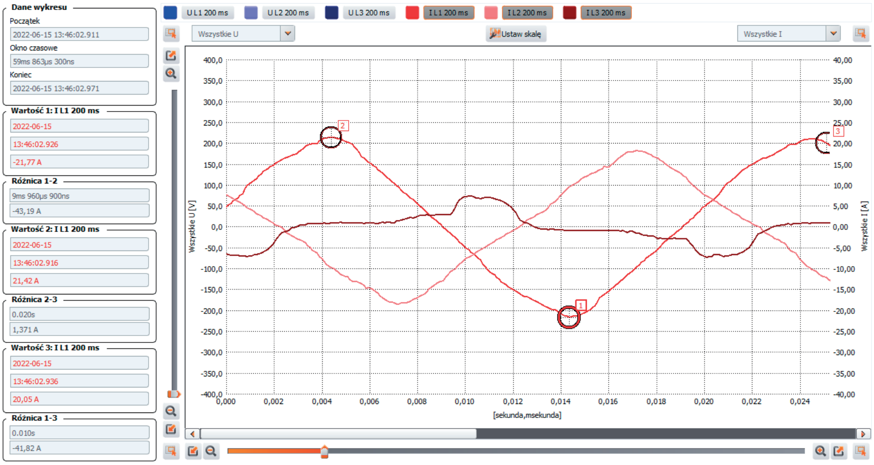

Fig. 13. Current waveforms recorded at normal operation of the electrical installation

Source: own study

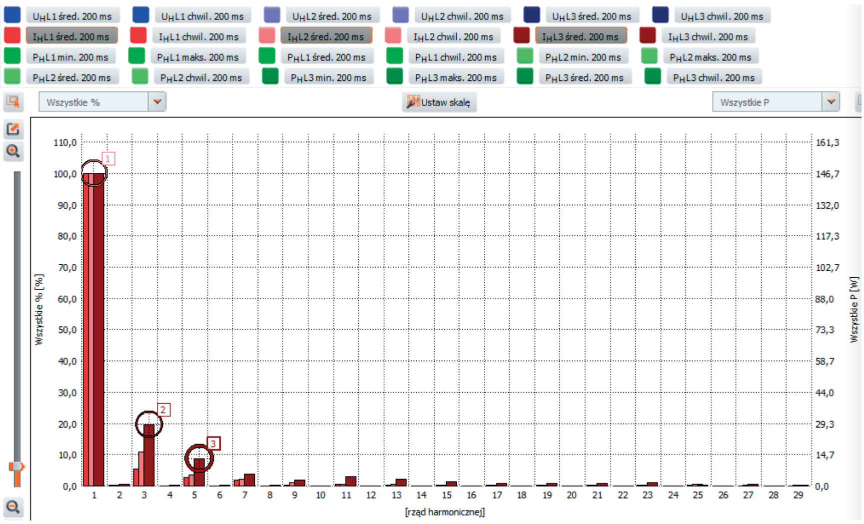

Fig. 14. Current harmonics recorded at normal operation of the electrical installation

Source: own study

4. Results interpretation

The impact on the safety of transformer operation will be illustrated for the results obtained for stage (C) of the tests. Calculations for other stages were omitted and will be developed in further research.

For the most deformed phase (1), the peak current recorded was 5.5 A. After numerical integration, the RMS value of the waveform was equal to 1.66 A.

By transforming formulas (7) and (8), the relationship (9) was obtained:

$$P = \frac{\pi^2 d^2}{6\rho D} \cdot B_p^2 \cdot f^2 = \frac{\pi^2 \mu^2 d^2 N^2}{6\rho D l^2} \cdot I^2 \cdot f^2 = K_0 I^2 f^2 \tag{9}$$

where: K_0 – constant depending on the geometrical and environmental parameters of the transformer windings.

For the peak value mentioned earlier, for an undistorted sine wave (fundamental component) the loss will be:

$$P_{50} = 6\,925\ K_0\ \text{W/kg} \tag{10}$$

For the determined shares of successive harmonics (the calculations are limited to the 3rd, 5th and 7th harmonics), the losses will be, respectively:

$$P_{150} = 20\,966\ K_0\ \text{W/kg} = 3.03 \cdot P_{50} \tag{11}$$

$$P_{250} = 22\,436\ K_0\ \text{W/kg} = 3.24 \cdot P_{50} \tag{12}$$

$$P_{350} = 17\,950\ K_0\ \text{W/kg} = 2.59 \cdot P_{50} \tag{13}$$

Consequently:

$$\frac{P_{150} + P_{250} + P_{350}}{P_{50}} = 8.86 = K \tag{14}$$

This means that in a given device, the power of eddy current losses, with the measured harmonics, is a significant factor influencing the functioning of the transformer.

According to equation (5), the same result is obtained:

$$K = \sum_{i=1}^{n} \left(h_i\right)^2 (n)^2 = 0.58^2 \cdot 3^2 + 0.36^2 \cdot 5^2 + 0.23^2 \cdot 7^2 = 8.86 \tag{15}$$

5. Discussion

The above estimates contain several simplifying assumptions:

- The distorted currents affect the transformer.
- Calculations were made only for the first three odd harmonics.
- There is no element in the system that could affect the filtering of waveforms described above.

This means that the estimates are for extreme working conditions and the actual values may be much lower. Nevertheless, with such a power loss level resulting from the recorded current waveform deformations, this phenomenon is not negligible and may significantly affect the value of eddy currents in network transformers.

There is a need for large-scale research aimed at developing the scope of research presented in the article. The growing number of non-linear receivers means that the safety of using power transformers is at risk.

Although this article deals with the influence of higher harmonics on power transformers, the effects of their influence on the reactive power compensation systems (capacitors) are known. This phenomenon is equally dangerous and may lead to the failure of capacitors. If such a situation takes place shortly after periodic inspections of the electrical system, the risk of a fire due to damage to the capacitors increases.

6. Conclusions

Based on an analysis of literature, the measurements taken and their interpretations, the following conclusions can be drawn:

- Eddy currents are the cause of power losses in electrical devices and are minimized by, inter alia, the method of core construction, metal alloys used and packeting of core sheets.
- The eddy currents depend on values of the currents flowing in the transformer windings, and also on the frequency.
- The contribution of higher harmonics, generated by non-linear devices connected to the network, can significantly affect the eddy currents and thus lead to an increase in the temperature of the transformer core.
- A transformer that is too hot can lead to an emergency situation, including a fire. There are real indications that the excessive share of non-linear loads may pose a threat despite the fact that the rated parameters of the transformer are not exceeded [14].
- The obtained results, based on the calculation algorithm described in the literature [8], prove that non-linear current receivers significantly affect the

operational safety of power transformers. The obtained values of the coefficients refer to the theoretical situation, taking into account many simplifying assumptions, but the scale of the phenomenon cannot be neglected.

- There are known methods of reducing the influence of higher harmonics for the purpose of improving the working conditions (and safety) of power substations [15, 16]. Such methods should be widely researched and implemented in practice.

7. References

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