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Chapter 8
The impact of electric energy receivers used in modern households on energy efficiency in the low-voltage network

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This paper deals with the issues of power losses in low-voltage supply networks caused by the impact of electricity loads in modern households. These power losses have a direct impact on energy efficiency. The authors analyze the influence of reactive power and higher harmonics and base their considerations based on the studies which include typical modern household receivers. Based on the measurement results for single receivers and simple formulas, approximate losses in low-voltage networks are presented. The final results show the need for further analysis of the topic, preceded by a more complex computer simulation.

Index terms: energy efficiency, higher harmonics, household receivers, reactive power

Introduction

A typical home user of electrical equipment when choosing a receiver, e.g. a light source, pays attention to active power consumption. This is reasonable because this parameter will affect the amount on the electricity bill. The fact is that active power consumption of typical household appliances has decreased. A good example is the transition from incandescent light sources (e.g. a traditional light bulb) to LED sources, where active power consumption has been reduced many times while maintaining a similar luminous flux value. However, the use of LED sources and an increasing number of electronic receivers that use impulse power supplies bring an increase in reactive power consumption and deformation power, which results from the deformed nature of the current. This paper presents the possible effects of using electricity receivers that are present in the modern household, which brings the issue of energy efficiency.

Increase in active power losses caused by the flow of reactive power

To understand the mechanism of increase in active power caused by the flow of reactive power, considerations should start with the relationship between active, reactive power and apparent power. These relationships are presented in equation 8.1 and Figure 8.1 [1]:

$$S = \sqrt{P^2 + Q^2}\ , \tag{8.1}$$

where:
S – apparent power,
P – active power,
Q – reactive power.

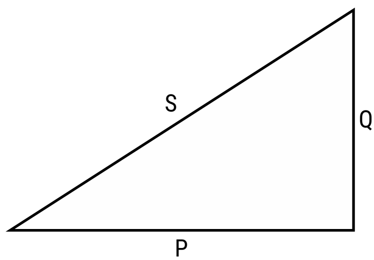

FIGURE 8.1. **Power triangle**

Analyzing equation (1) and Figure 8.1, it can be observed that an increase of active power P or reactive power Q causes an increase of apparent power S. The value of apparent power defines the RMS value of the current flowing through the grid according to the relation form equation (2):

$$I = \frac{S}{U}\ , \tag{8.2}$$

where:
I – RMS value of current intensity,
U – RMS value of voltage.

Active power losses resulting from the presence of resistance of the three-phase low-voltage network can be calculated based on equation (8.3) [2, 3, 4, 5, 6, 7]:

$$\Delta P = 3 \cdot I^2 R = \frac{P^2 + Q^2}{U^2} \cdot R = \frac{P^2 \cdot \left(1 + \mathrm{tg}^2 \varphi\right)}{U^2} \cdot R, \tag{8.3}$$

where:
ΔP – active power losses,
R – resistance of single-phase wire,
$\mathrm{tg}\varphi$ – power factor (tangent).

Here it can be seen that an increase in reactive power will result in an increase in apparent power and thus in a value of effective current. A loss of active power in a grid resistance is proportional to the square of this value. Equation (3) also shows the dependance of these losses on the power factor in the form of tangents. The formula (8.4) [8] and Figure 8.2 show a relative increase of active power losses based on the power factor in the form of cosine.

$$\delta\Delta P_Q = \mathrm{tg}^2\varphi \cdot 100\% = \left(\frac{1}{\cos^2\varphi} - 1\right)\cdot 100\%, \tag{8.4}$$

where:

$\delta\Delta P$ – relative increase of active power losses caused by reactive power flow,

$\cos\varphi$ – power factor (cosine).

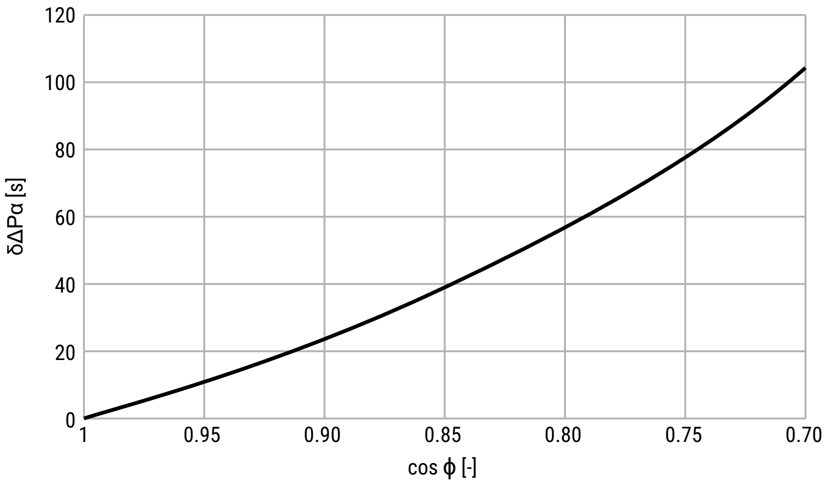

FIGURE 8.2. Characteristics of relative increase of active power loss as a function of power factor values

With a power factor of 0.82, active power losses increase by 50% compared to no reactive power state, and with a value of 0.71 – an increase by 100%.

In addition to the active power losses in the resistance of household power supply cables, there is also an increase in the load active power losses in the power supply transformer, resulting from the flow of the current with a higher RMS value through transformer windings which, like power supply cables, have their resistance.

Increase in active power losses caused by the flow of distorted current

A. Increase in active power losses caused by increase in apparent power

The effects of reactive power flow associated with an increase in RMS value of the current become more pronounced when dealing with distorted current consumption. The power triangle in Figure 8.1 is then supplemented for deformation power, which modifies the mentioned figure to the spatial form of the so-called power cuboid [9] presented in Figure 8.3.

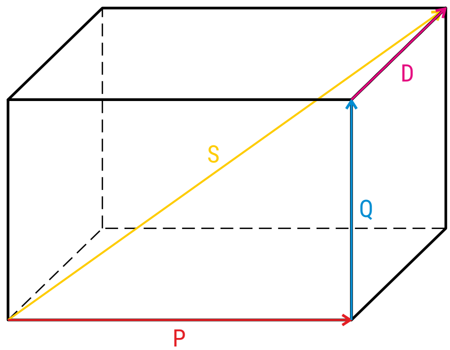

FIGURE 8.3. **Power cuboid**

The apparent power can then be determined by means of formula (8.5):

$$S = \sqrt{P^2 + Q^2 + D^2}, \tag{8.5}$$

where:
D – deformation power.

The mechanism of increasing active power losses is analogous to the previous point of the paper.

B. Impact of higher harmonics on wire losses

When analyzing the impact of higher harmonics, two points should be noted:

- skin effect,
- summation of higher harmonics of every third order in a neutral wire N or protective earth neutral wire PEN.

A skin effect is an increase in the resistance of a wire for high frequency currents. A higher frequency causes that the flow is not uniform throughout the cross-section. The density of the current in the middle of the cross-section decreases, which makes it practically inactive and the density in the part distant from the middle of the cross section increases. The useful cross-section of the wire is reduced, which results in the resistance increase depending on the height of frequency of the flowing current according to formula 8.6 [10, 11]:

$$R_h = \delta_{Rh} \cdot R_{DC} \approx \sqrt{h} \cdot R_{DC}, \tag{8.6}$$

where:

R_h – wire resistance for h-th harmonic flow,
δ_{Rh} – wire resistance gain factor for h-th harmonic flow,
R_{DC} – wire resistance for DC current,
h – harmonic order.

An increase in resistance for a given current RMS value will lead to an increase in active power losses in the wires where the current containing higher harmonics will flow, as shown by formula 8.7 [10]:

$$\Delta P = \sum_{h=1}^{\infty} \left(R_h \cdot I_h^{\ 2} \right), \tag{8.7}$$

where:

I_h – RMS value of current intensity of h-th harmonic.

When considering a power supply consisting of three-phase wires and a neutral wire, formula (8.7) can be modified to (8.8) [11]:

$$\Delta P = R_{DC} \cdot \sum_{h=1}^{\infty} \left[\sqrt{h} \cdot \left(I_{hL1}^{\ 2} + I_{hL2}^{\ 2} + I_{hL3}^{\ 2} + I_{hN}^{\ 2} \right) \right], \tag{8.8}$$

where:

$I_{h_{L1,L2,L3,N}}$ – RMS value of current intensity of h-th harmonic in individual wires.

Based on the fact that active power losses, in the absence of higher harmonics, are caused by the first harmonic, it is possible to present a relative increase of active power losses caused by the flow of distorted current by means of relation (8.9) [11]:

$$\delta \Delta P = \frac{\sum_{h=2}^{\infty} \left[\sqrt{h} \cdot \left(I_{h_{L1}}^2 + I_{h_{L2}}^2 + I_{h_{L3}}^2 + I_{h_N}^2 \right) \right]}{I_{1_{L1}}^2 + I_{1_{L2}}^2 + I_{1_{L3}}^2 + I_{1_N}^2}, \tag{8.9}$$

where:

$\delta \Delta P$ – relative increase of active power losses caused by the flow of distorted current.

Focusing on a single phase, a relative increase in active power losses in a single phase can be presented using formula (8.10):

$$\delta \Delta P = \frac{\sum_{h=2}^{\infty} \left(\sqrt{h} \cdot I_{h_{L1}}^2 \right)}{I_{1_{L1}}^2}. \tag{8.10}$$

Another phenomenon that increases the losses of active power is the accumulation of h-th higher harmonics of the current in the N or PEN wire. They form symmetrical systems of the zero order [12], which makes it possible that in the situation when identical single-phase receivers are connected to three different phases, in a neutral wire e.g. a third harmonic with the amplitude being the sum of the harmonic amplitudes of the third harmonics of individual receivers will be present, as shown by formula (8.11) and Figure 8.4 [13]. Such a situation would not occur if the mentioned receivers were linear. By combining the summation of the mentioned harmonics and the skin effect, it can be observed that an increase of active power losses in the N or PEN wire can be significant.

$$I_{\mathrm{N}} = I_{\mathrm{R}} + I_{\mathrm{S}} + I_{\mathrm{T}} = \sum_{\mathrm{n}=1}^{\infty} \left[I_{\mathrm{R(3n)}} + I_{\mathrm{S(3n)}} + I_{\mathrm{T(3n)}} \right], \tag{8.11}$$

where:

n – natural number,

$I_{\mathrm{R(3n)}}$ – RMS value of current intensity of 3n-th harmonic in R-phase wire,

$I_{\mathrm{S(3n)}}$ – RMS value of current intensity of 3n-th harmonic in S-phase wire,

$I_{\mathrm{T(3n)}}$ – RMS value of current intensity of 3n-th harmonic in T-phase wire.

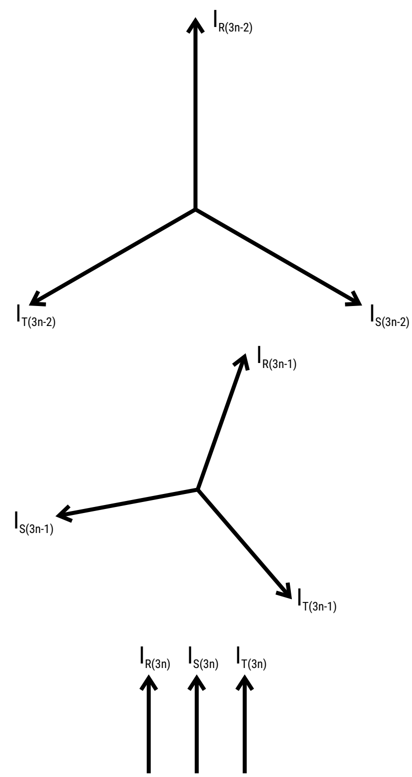

FIGURE 8.4. Relationship between successive harmonics in three phases

C. Impact of higher harmonics on transformer losses

Just like in the wires, one of the reasons for the increase in active power losses in a transformer is the skin effect, which increases the resistance of its windings. Additionally, the presence of higher harmonics causes an increase in core losses from eddy currents and hysteresis losses [14].

The influence of eddy currents on the losses of active power can be presented by means of the K factor described in relation (8.12), which refers to the ratio of these losses in the course of a deformed current flow to losses during sinusoidal flow [15].

$$K = \frac{1}{I_{rms}} \sum_{h=1}^{\infty} \left[I_h^2 \cdot h^2 \right], \tag{8.12}$$

where:

I_{rms} – RMS value of current intensity

ANALYSIS OF CURRENTS AND POWER RECEIVED BY SELECTED HOUSEHOLD RECEIVERS

A. Measurement results

To make the measurements, the Sonel PQM-701 power quality meter was applied. For this purpose, the measuring system with the diagram shown in Figure 8.5 was used [13, 16].

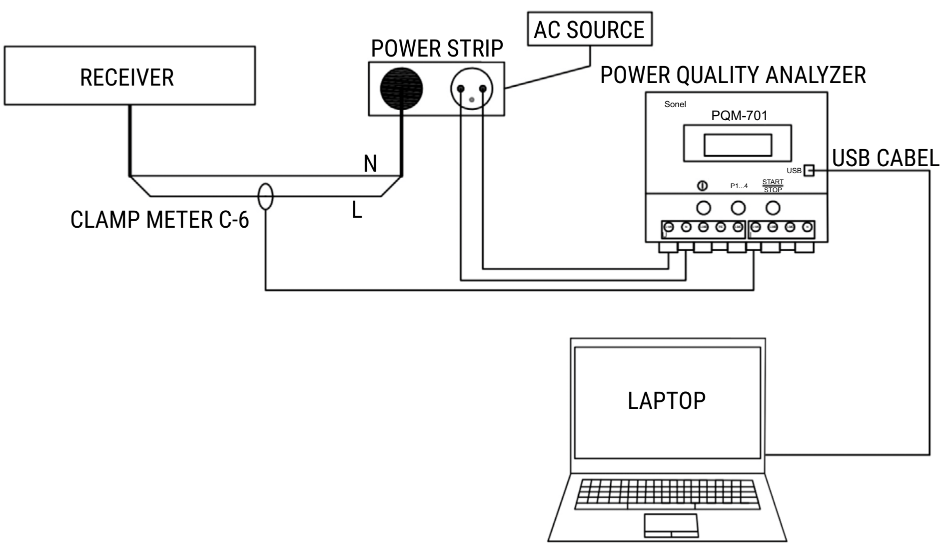

FIGURE 8.5. Diagram of the measuring system

The measurement of a single receiver lasted about one minute and included several 10-second measurement cycles. One of the middle cycles was selected in order to avoid the influence of transient states during switching on and off the tested devices. During the measurement, selected electrical parameters as well as current and voltage waveforms were recorded.

Table 8.1 presents the results of measurements of electrical parameters of selected, representative receivers in a typical household. Reactive power marked with a minus means it has a capacitive character.

Figures 8.7 – 8.12 present current waveforms of selected receivers and their harmonic spectra. More receivers were overviewed in [13].

TABLE 8.1 Values of active power, reactive power, deformation power, complex power, power factor PF (cosine) and total distortion factor of current THD_i

Device	P [W]	Q [var]	D [var]	S [VA]	PF [–]	THDi [%]
Satellite receiver	17.14	-6.77	28.59	34.02	0.51	152.43
Home Cinema	39.94	-1.70	61.29	72.85	0.54	152.69
Smartphone charger No. 1	13.35	-2.05	20.41	24.47	0.55	147.76
Smartphone charger No. 2	6.94	-1.44	10.08	12.32	0.56	138.54
Tablet charger	12.60	-3.24	20.65	24.40	0.52	155.86
Video game console	112.10	-32.44	39.67	123.25	0.91	34.04
Compact fluorescent lamp	8.00	-3.94	9.55	13.07	0.61	107.31
LED lamp No. 1	6.27	-7.06	7.21	11.88	0.53	75.40
LED lamp No. 2	12.40	-5.30	15.92	20.86	0.60	117.91
Laptop No. 1	8.00	-8.04	21.50	24.31	0.33	187.32
Laptop No. 2	13.40	-6.62	28.73	32.38	0.41	183.35
Desktop computer	72.87	4.34	74.51	104.31	0.70	101.97
LCD monitor	40.00	-6.08	61.40	73.53	0.54	149.99
LCD TV	135.69	-46.61	27.79	146.14	0.93	19.80
LED TV	44.00	-11.99	68.04	81.91	0.54	147.21

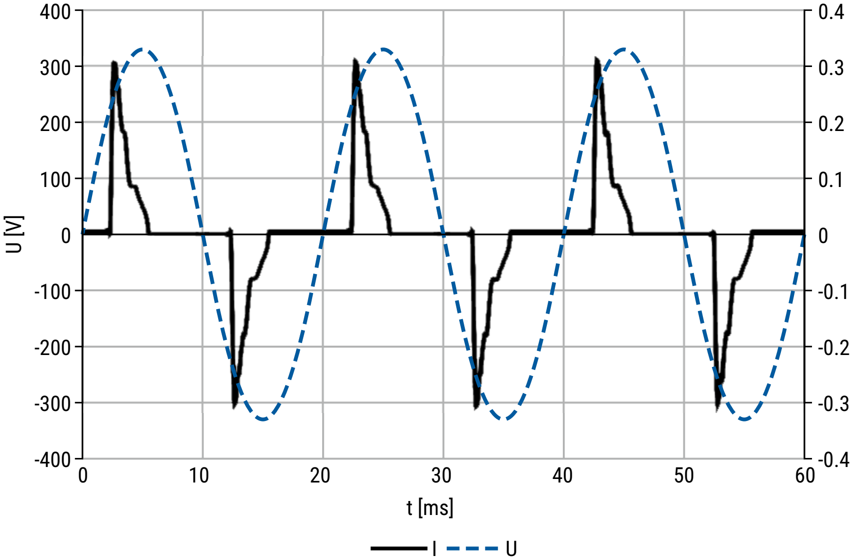

FIGURE 8.6. Current and voltage waveforms for LED source

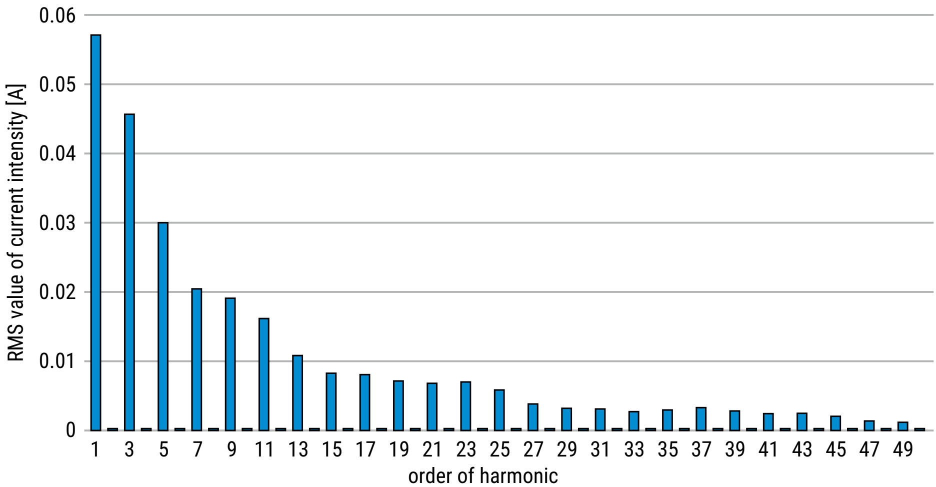

FIGURE 8.7. Harmonic spectrum of current received by LED source

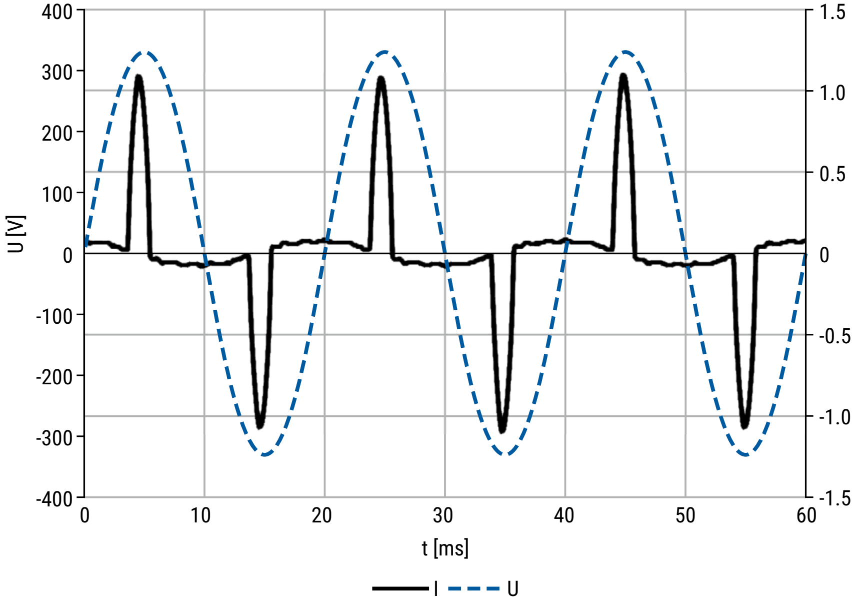

FIGURE 8.8. Current and voltage waveforms for LED TV

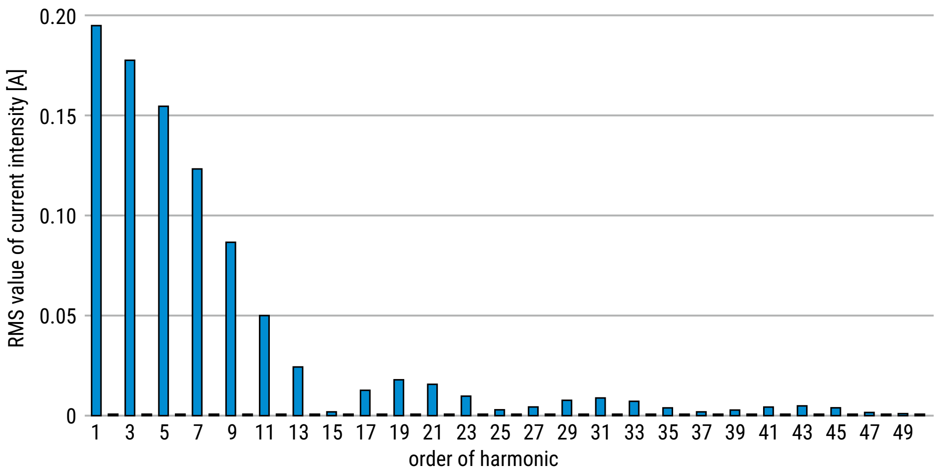

FIGURE 8.9. Harmonic spectrum of current received by LED TV

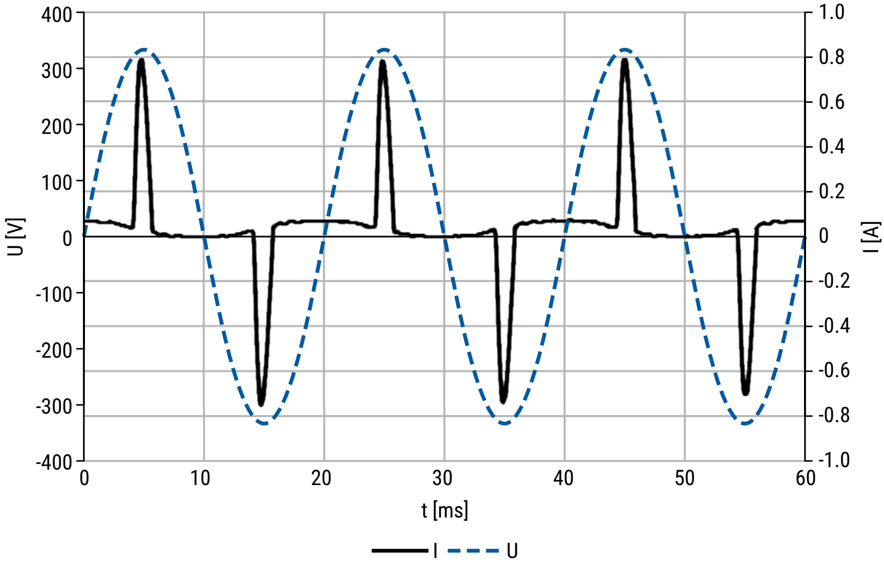

FIGURE 8.10. Current and voltage waveforms for laptop

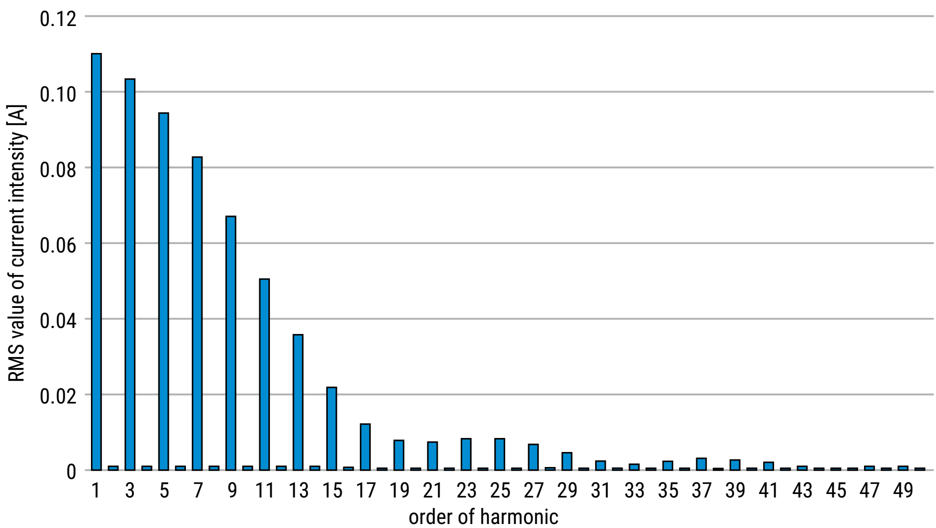

FIGURE 8.11. Harmonic spectrum of current received by laptop

B. Analysis of measurement results

Most of the receivers presented above receive strongly distorted current, as evidenced by the THDi value exceeding 100%. 13 out of 17 receivers presented in Table 8.1. This consumed more of the deformation power than the active power and in case of laptops more than twice as much. Figures 8.7, 8.9 and 8.11 show that in the harmonic spectrum of received impulse currents, mainly odd harmonics are present, whose amplitude decreases with a harmonic order increase. The third harmonic has the highest value, and a significant value of the ninth harmonic can also be observed.

Capacitive reactive power consumption is also noticeable, which is about 25% of the value of the active power consumption of the presented set of receivers.

To observe the approximate effect of reactive power consumption and deformed current on active power losses, calculations were made on the basis of formulas (4) and (10), the results of which are presented in the tabular Table 8.2. The calculation assumes that the resistance of circuit is 1.5 Ω.

TABLE 8.2 The results of calculations presenting the approximate influence of modern receivers on the loss of active power in power supply wires

Device	cosφ [–]	$\delta\Delta P_Q$ [%]	$\delta\Delta P_h$ [%]	ΔP [mW]	ΔP_Q [mW]	ΔP_h [mW]
Satellite receiver	0.93	13.50	553.83	8.33	1.12	46.14
Home Cinema	1.00	0.18	532.91	45.23	0.08	241.05
Smartphone charger No. 1	0.99	2.30	521.88	5.05	0.12	26.37
Smartphone charger No. 2	0.98	4.13	494.12	1.37	0.06	6.75
Tablet charger	0.97	6.20	658.20	4.50	0.28	29.63
Video game console	0.96	7.73	21.34	356.33	27.53	76.04
Compact fluorescent lamp	0.90	19.52	271.12	1.81	0.35	4.92
LED lamp No. 1	0.66	55.91	119.69	1.11	0.62	1.33
LED lamp No. 2	0.91	15.45	336.01	4.36	0.67	14.65
Laptop No. 1	0.71	50.25	1043.49	1.81	0.91	18.94
Laptop No. 2	0.90	19.62	887.98	5.09	1.00	45.21
Desktop computer	1.00	0.35	206.78	150.57	0.53	311.34
LCD monitor	0.99	2.26	511.42	45.37	1.02	232.02
LCD TV	0.95	10.55	7.88	522.07	55.10	41.14
LED TV	0.96	6.91	491.13	54.90	3.79	269.61
Total				1207.91	93.21	1365.15

It should be emphasized that the results of the calculations presented in Table 8.2 in the case of reactive power are reliable. However, in the case of harmonic influence they are approximate due to the complexity of the problem, which in the presented solutions is considered in a simplified way using the assumption that the increase of resistance for a given harmonic is proportional to $\sqrt{h}$.

Conclusions

The presented measurement results show that electrical energy receivers in a modern household – despite low active power consumption – entail passive and deformation power consumption, the latter of which, by significant values, has a noticeable impact on the value of apparent power. As mentioned in the theoretical part, an increase in apparent power is equivalent to an increase in the effective current value and thus losses of active power in the resistance of the wires of the low--voltage network and the transformer windings. However, the theoretical considerations based on measurements of single receivers are not reliable because while the reactive power can be summed up, for the deformation power it is not as simple, which can be observed in [13], where separate measurements of two single LED sources and measurements of the same sources switched on simultaneously are presented. You can see that while the sum of the reactive power is similar, the sum of the deformation power already diverges. This is due to the fact that harmonics of the same order in two different receivers may have a different phase shift and thus the resultant spectrum will look different.

In order to take into account the approximate influence of higher harmonics, calculations were made based on the effective values of individual harmonics included in [13]. The results are presented in Table 8.2 together with the results of calculations of active power losses resulting from reactive power. The losses of active power caused by the flow of reactive power and deformed currents received by the selected set of receivers may amount to about 120% of the active power losses present in the absence of the mentioned phenomena. Assuming that similar devices are present e.g. in a housing estate consisting of 500 apartments, these losses may amount to approx. 700 W in the wires alone. It should be noted, however, that the increase of power losses from the flow of distorted current, which is the main component of additional losses, was calculated using the simplification of the proportionality of the conductor resistance to $\sqrt{h}$, which could overstate the obtained result.

It should be noted that losses are not limited to wires only. A sensitive device is also the transformer, which, nonetheless, was not included in the above calculations.

The presence of the 3rd and 9th harmonics can additionally increase these losses in the N or PEN wire because the harmonics of these orders can accumulate there.

From the analysis of the presented measurement results it can be concluded that modern electricity receivers commonly used in households, despite the low consumption of active power, are characterized by a noticeable consumption of reactive power and distorted current. A single household is not a big problem, but when all the apartments are added together, e.g. housing estates, these values can reach a high level. As mentioned in the previous paragraph, theoretical considerations can only outline the problem, due to the difficulty of interpreting individual results.

However, this urges the need to inspect the actual values of individual power and current flows consumed by individual apartments, blocks of apartments or housing estates in order to verify the real scale of the influence of modern households on energy efficiency.

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