

Article

The Influence of Subsequent Harmonics of the Load Current on Errors of Electronic Energy Meters

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Abstract: In the electrical installations of buildings, there is an increasing number of non-linear energy receivers, which introduce strong distortions of the load current of electronic energy meters. Since the readings of these meters are the basis for financial settlements of electricity consumers, it is very important to determine how much the distortion of the receiver current affects the correct operation of commonly used electronic energy meters. The article will present exemplary results and analyses of research work on the impact of individual current harmonics on the readings and errors of selected energy meters.

Keywords: energy measurement; non-linear load; load current harmonics; energy meter; total harmonic distortion



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1. Introduction

Electronic energy meters are designed to measure active and reactive energy consumed by various receivers. In the electrical installations of buildings, there is an increasing number of non-linear loads, which introduce strong distortion of the current measured by energy meters. Since the readings of these meters are the basis for financial settlements of electricity consumers, it is very important to determine how much the distortion of the receiver current affects the correct operation of commonly used electronic energy meters. The answer to the above question can be sought both in the power theory and by performing appropriate research, especially analysis of the impact of individual current harmonics on the readings of selected energy meters. The latter includes primary analysis of the influence of the value of the current as well as its total harmonic distortion (THD) on errors of various electronic energy meters.

The widespread use of energy-saving loads that are highly non-linear in both utility distribution systems and households continues to spread due to the implementation of energy-saving policies [1]. These nonlinear energy receivers can strongly distort the alternating current (AC) flowing through them [2–6]. Current distortion can, in turn, deteriorate the accuracy of measured electrical energy which is most often measured using electronic energy meters (Figure 1), which work differently than electromechanical meters and also respond differently to load current deformations.

In electronic energy meters, analog AC signals are digitized using precise analog-to-digital converters (ADCs) into their binary representation, i.e., into sequences of binary numbers. Then, both current and voltage signals are processed using algorithms developed by the meter manufacturer. Algorithms for processing measurement signals are based on modern achievements of power theory [7] and are usually a trade secret. The CPU unit (Figure 1) is responsible for calculating instantaneous power values, which are integrated at specific time intervals. The measured signals are processed so that the energy signal also reflects the higher harmonics of a specific band that appear in the input waveform. During the research, attention was focused on the fact that there are many different technical

solutions of electronic energy meters [8–11], which differ in both construction details and implemented signal processing algorithms. The following part of our paper will present the measurement results for three selected types of electronic energy meters commonly used in home installations.

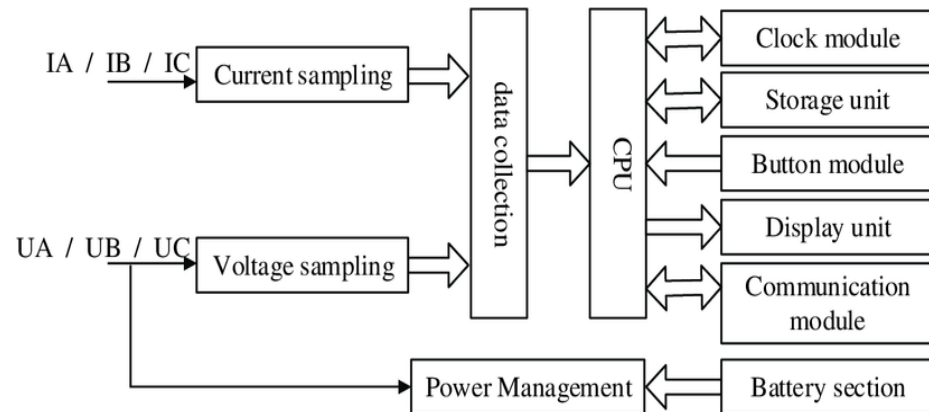


Figure 1. Block schematic diagram of a typical electronic energy meter.

Energy meters should be designed to correctly measure the energy consumption of various loads. The number of non-linear loads (e.g., switching power supplies, discharge lamps, LED lamps, etc.) is constantly growing. As mentioned above, loads of this type introduce strong current distortions. It was shown that modern, approved electronic energy meters may incorrectly measure the energy consumed by energy-saving loads [12]. Currently, many studies [13–16] are being conducted to estimate the losses of both suppliers and consumers of electricity, which depend, among others, on the energy consumption profile.

This work describes in detail research related to determining how alternating current distortions affect the operation of measuring instruments used in smart grids. This problem can be solved in various ways—for example, by applying power theory or by conducting appropriate measurement experiments. In this article, which is an extension of work [17], after determining the basic parameters and methodology used in the study, the results of measurement errors of sample electronic energy meters for load currents with various distortion content are described.

Currently, electronic meters are usually equipped with communication interfaces that allow the use of this type of devices in smart grid systems [17–20]. Electronic energy meters are more functional, resistant to acts of sabotage, but are they more accurate or at least as accurate as electromechanical meters? This article will try to answer this question.

2. Basic Definitions

Even though the mains voltage is sinusoidal, the current is distorted due to the nonlinearity of the load on the power supply systems. The load nonlinearity mentioned in the work causes current distortions [21,22], which in commonly used power theories are represented by harmonic components I_n . The contribution of harmonic components to the load current can be represented by the formula:

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + \dots} = \sqrt{I_1^2 + \sum_{n=2}^{\infty} I_n^2}, \quad (1)$$

where I_n is the root mean square (RMS) value of the n th harmonic current. Taking into account load current distortions, the instantaneous power $p(t)$ can be represented by the following relationship:

$$p(t) = UI_1 \cos(\varphi_1)(1 - \cos(2\omega t)) - UI_1 \sin(\varphi_1) \sin(2\omega t) + \sum_{n=2}^{\infty} 2UI_n \sin(\omega t) \sin(n\omega t - \varphi_n) \quad (2)$$

where φ_n is the phase shift between the n th harmonic of the voltage and current. Additionally, in the equation expressing the apparent power S of the system, load current distortions can be taken into account using the formula:

$$S = UI = U \sqrt{I_1^2 + \sum_{n=2}^{\infty} I_n^2} \quad (3)$$

The apparent power can also be represented by an expression taking into account its components [23]:

$$\begin{aligned} S^2 &= U^2 I^2 = U^2 I_1^2 + U^2 \sum_{n=2}^{\infty} I_n^2 = \\ &= S_1^2 + H^2 = P_1^2 + Q_1^2 + H^2 = P_1^2 + D^2 \end{aligned} \quad (4)$$

where P_1 and Q_1 are the active and the reactive power of the fundamental, H is the deformation power, and D is the distortion power. The geometric relationship between the power vectors presented in Equation (4) is shown in Figure 2.

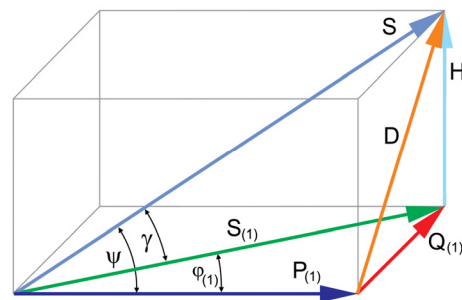


Figure 2. Geometric relation between power component vectors.

The relationships between power components can also be presented in the form of an equation describing the power factor PF :

$$PF = \frac{P_1}{S} = \frac{P_1}{\sqrt{S_1^2 + H^2}} = \frac{P_1}{\sqrt{P_1^2 + Q_1^2 + H^2}} \quad (5)$$

The amount of load current distortion, which translates into the amount and harmonic content of the distorted alternating current, can be expressed in terms of the total harmonic distortion coefficient:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (6)$$

3. Method for Determining Errors in Energy Meters

All energy meters belong to the group of measuring instruments subject to verification sometimes called “primary verification” or “verification” [24]. In accordance with the International Directive on Measuring Instruments (MID) 2014/32/EU [25], testing the accuracy of energy meters can be carried out using the control meter method or the power-time method. In accordance with the guidelines of European normative acts, meter errors

are checked for various load currents, but only for sinusoidal currents. It is not necessary to determine meter errors for non-linear loads causing current distortions. In the literature, descriptions of other measurement methods and procedures used to determine errors in energy meters can be found [26–31].

The Calmet C300 power calibrator [32] was selected to analyze the impact of distorted current waveforms on the readings of energy meters. This calibrator can simulate any pure or distorted AC voltage and AC current with any phase relationship between them. According to the diagram presented in Figure 3, the calibrator was used to supply current and voltage to a tested electronic energy meter.

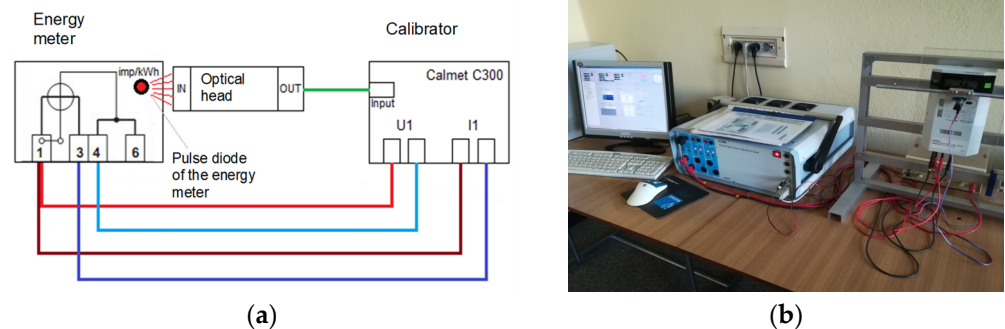


Figure 3. System for measuring errors of electronic energy meters: (a) block diagram of the system and (b) photo showing the system configuration.

The measurement procedure used to determine the errors of the tested energy meters consists of the following stages:

- The C300 calibrator generates the appropriate distorted supply current and voltage using the given amplitude and phase of each harmonic;
- The generated signals are used as current (I1–I3) and voltage (U1–U3) applied to the tested energy meter;
- The optical head (see Figure 3) detects the optical pulses from the tested energy meter, converts them to electrical pulses and sends them to the calibrator;
- The software running on a PC computer controlling the C300 calibrator (Figure 4) records the energy indicated by the tested meter using the power method over time;
- Finally, using the CALPRO 300 v.1.3.0 program, the energy measurement error is calculated as the difference between the energy measured by the meter (device) under test (DUT) and the actual energy generated by the calibrator.

Energy meter errors can be calculated from the equation:

$$\varepsilon = \frac{E_m - E_c}{E_c} \cdot 100\% \quad (7)$$

where E_m is energy measured by the meter and E_c is energy generated by the calibrator.

The uncertainty of energy generation of the C300 calibrator is $\pm 0.005\%$, which is why further measurement results are given with such precision.

For all phases (I1–I3) the same current distortions were generated.

During the tests, three methods of distorting load currents were used:

- (1) Only one harmonic (from the 2nd up to the 31st) was added to the signal containing only the fundamental;
- (2) Multiple subsequent harmonics were added with no phase shift relative to the fundamental, with subsequent odd harmonics of amplitudes decreasing from 100% to 10% and even harmonics with amplitudes equal to 3% of the fundamental;
- (3) Multiple subsequent harmonics were added with different phase shift relative to the fundamental, with subsequent odd harmonics of amplitudes decreasing from 100%

to 10% and even harmonics with amplitudes equal to 3% of the fundamental. Phase shifts were modeled on the example of a specific load—LED lamps).

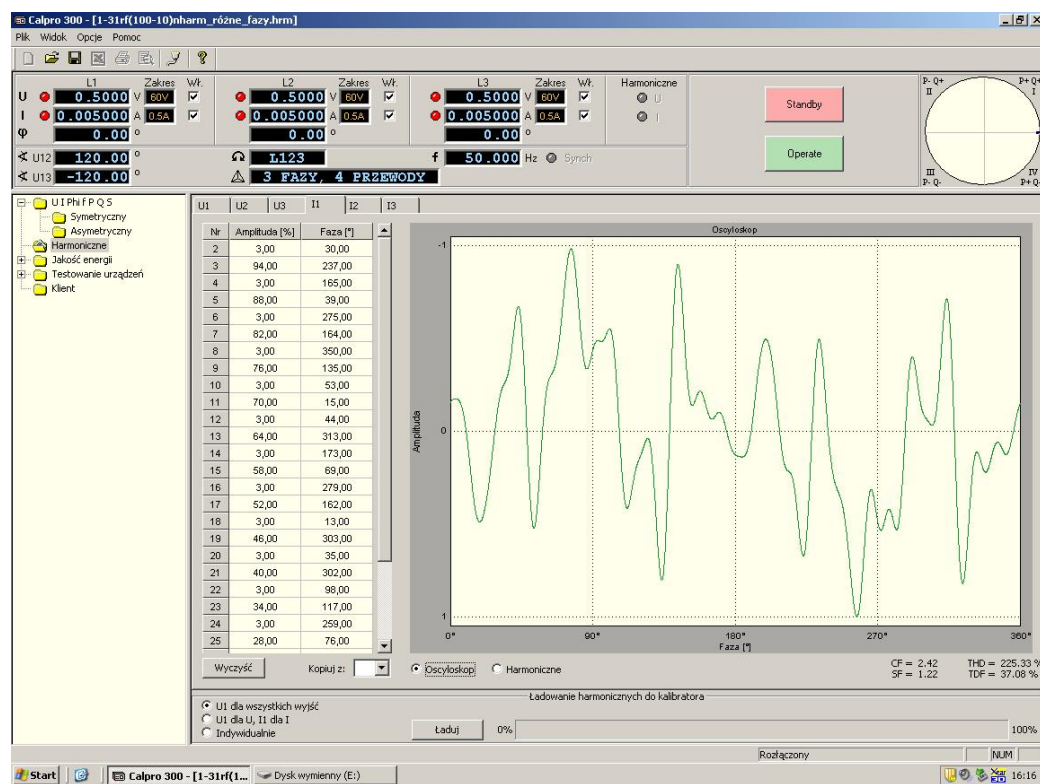


Figure 4. Screenshot of the CALPRO 300 program with an example graph of the generated distorted current.

In Method 1, it was checked whether energy meters are sensitive to specific harmonics of the distorted load current. Method 2 checked whether the meter errors are determined by the level of load current distortion (THD). The subsequent harmonics added had a contribution typical for the specific loads previously tested. However, in Method 3, the phase shifts of individual harmonics were additionally taken into account so that the test signal was similar to the load currents for typical loads such as LED lamps. Previous research had shown that energy meters are particularly sensitive to load currents generated by LED lighting [7].

The presented procedure can be used to test various types of energy meters: electromechanical, electronic and other meters using microcontrollers or other processing units. The main advantage of this method is the use of a programmable calibrator, which eliminates the need to perform measurements using real loads. Several different electronic energy meters were tested, used both for billing and in building automation systems and balancing of renewable energy sources. The next chapter presents selected measurement results.

4. Results and Discussion

The characteristic distortions of the load currents were set using the Calpro computer software working with the Calmet C300 calibrator (Figure 3). This software enables, among others: determining errors of tested meters using the power and time method without the need to have a control meter for both sinusoidal and distorted currents, taking into account the influence of individual harmonics.

The results of the conducted research allow determination of the impact of individual harmonics of the load current on the errors of electronic energy meters and assessment of the correctness of their operation.

The research was carried out in accordance with the three previously described methods, and the results of these studies will be presented in the next three subsections.

4.1. Method 1—Current Distortion Caused by a Single Consecutive Harmonic

Method 1 involves distorting the current flowing in phase wires of the energy meter's current circuits by selectively introducing subsequent harmonics. The purpose of such a measurement procedure was to check whether the tested meters were particularly sensitive to specific harmonics.

Figure 5 shows an example load current spectrum with the selectively introduced 15th harmonic at 100% of the fundamental component.

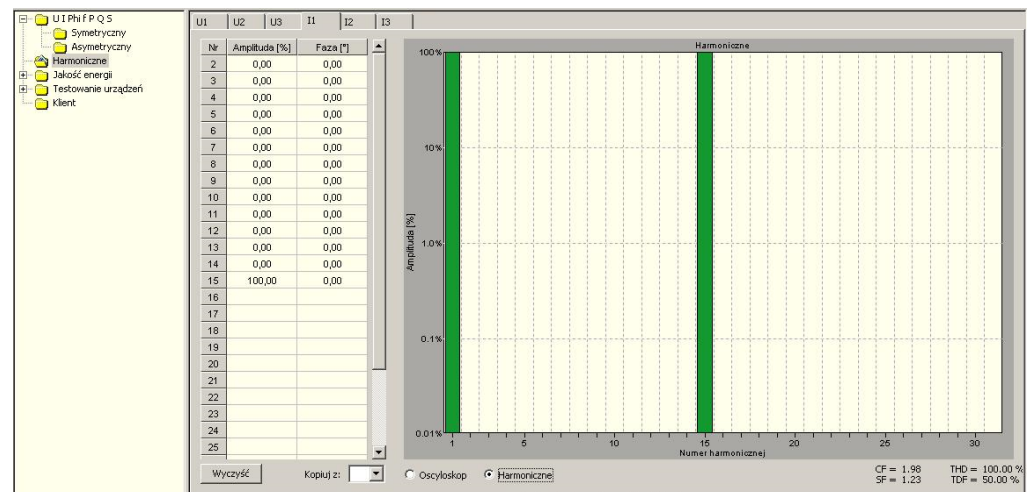


Figure 5. Screenshot of the CALPRO 300 shows load current spectrum with the selectively introduced 15th harmonic ($n = 15$).

Tables 1–5 present the errors of energy meters obtained with phase currents distorted by introduction of subsequent harmonics of the following amplitudes and phases:

- 10% of the fundamental current I_b , $\cos \varphi = 1$;
- 100% of the fundamental current I_b , $\cos \varphi = 1$;
- 100% of the fundamental current I_b , $\cos \varphi = 0.5$;
- 400% of the fundamental current I_b , $\cos \varphi = 1$.

Table 1. Summary of energy meters errors for sinusoidal load currents.

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	ϵ_1 , %	ϵ_2 , %	ϵ_3 , %	ϵ_1 , %	ϵ_2 , %	ϵ_3 , %	ϵ_1 , %	ϵ_2 , %	ϵ_3 , %
0.1 I_b , $\cos \varphi = 1$	−0.675	−0.703	−0.684	0.683	0.683	0.702	0.489	0.489	0.489
1 I_b , $\cos \varphi = 1$	−0.526	−0.526	−0.526	0.484	0.484	0.484	0.084	0.094	0.103
1 I_b , $\cos \varphi = 0.5$	−0.232	−0.512	−0.593	2.705	2.712	2.732	−1.758	−1.721	−1.684
4 I_b , $\cos \varphi = 1$	−0.583	−0.583	−0.583	0.345	0.346	0.353	−0.412	−0.450	−0.334

Table 2. Summary of energy meters errors for distorted load currents (100% of the second harmonic).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	ϵ_1 , %	ϵ_2 , %	ϵ_3 , %	ϵ_1 , %	ϵ_2 , %	ϵ_3 , %	ϵ_1 , %	ϵ_2 , %	ϵ_3 , %
0.1 I_b , $\cos \varphi = 1$	−0.769	−0.735	−0.719	0.761	0.741	0.741	0.489	0.450	0.450
1 I_b , $\cos \varphi = 1$	−0.431	−0.450	−0.460	0.562	0.567	0.571	0.508	0.770	0.113
1 I_b , $\cos \varphi = 0.5$	−1.265	−1.279	−1.256	2.002	1.982	1.935	−1.933	−1.906	−1.920
4 I_b , $\cos \varphi = 1$	−0.355	−0.355	−0.431	0.404	0.399	0.400	−0.593	−0.562	−0.504

Table 3. Summary of energy meters errors for distorted load currents (100% of the third harmonic).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	ε_1 , %	ε_2 , %	ε_3 , %	ε_1 , %	ε_2 , %	ε_3 , %	ε_1 , %	ε_2 , %	ε_3 , %
0.1 I_b , $\cos\varphi = 1$	−0.719	−0.719	−0.700	0.761	0.761	0.761	0.567	0.528	0.567
1 I_b , $\cos\varphi = 1$	−0.545	−0.517	−0.536	0.678	0.688	0.678	0.075	0.075	0.065
1 I_b , $\cos\varphi = 0.5$	−1.284	−1.331	−1.391	2.084	2.044	2.014	−1.800	−1.786	−1.772
4 I_b , $\cos\varphi = 1$	−0.393	−0.431	−0.469	0.431	0.417	0.416	−0.563	−0.637	−0.609

Table 4. Summary of energy meters errors for distorted load currents (100% of the 30th harmonic).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	ε_1 , %	ε_2 , %	ε_3 , %	ε_1 , %	ε_2 , %	ε_3 , %	ε_1 , %	ε_2 , %	ε_3 , %
0.1 I_b , $\cos\varphi = 1$	−0.574	−0.656	−0.668	0.722	0.722	0.741	0.644	0.605	0.605
1 I_b , $\cos\varphi = 1$	−0.536	−0.536	−0.536	0.610	0.620	0.673	0.200	0.200	0.151
1 I_b , $\cos\varphi = 0.5$	−1.284	−1.298	−1.326	2.269	2.297	2.239	−1.998	−2.044	−2.021
4 I_b , $\cos\varphi = 1$	−0.621	−0.583	−0.583	0.301	0.267	0.256	−0.373	−0.572	−0.535

Table 5. Summary of energy meters errors for distorted load currents (100% of the 31st harmonic).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	ε_1 , %	ε_2 , %	ε_3 , %	ε_1 , %	ε_2 , %	ε_3 , %	ε_1 , %	ε_2 , %	ε_3 , %
0.1 I_b , $\cos\varphi = 1$	−0.775	−0.769	−0.744	0.567	0.586	0.586	0.296	0.296	0.257
1 I_b , $\cos\varphi = 1$	−0.545	−0.555	−0.564	0.349	0.354	0.354	0.123	0.094	0.103
1 I_b , $\cos\varphi = 0.5$	−1.410	−1.401	−1.438	1.957	1.905	1.877	−2.007	−2.081	−2.159
4 I_b , $\cos\varphi = 1$	−0.469	−0.507	−0.545	0.189	0.190	0.199	−0.569	−0.557	−0.540

This measurement procedure was inspired by the requirements regarding energy meters. Tests carried out for load currents higher than 400% of the fundamental current I_b ($\cos\varphi = 1$ and $\cos\varphi = 0.5$) did not show excessive errors in energy meters.

In all error tables presented in this work, error values that are greater than the permissible mark are marked in red. For all tested energy meters, the permissible values resulting from the class were 1%.

Tables 1–5 list errors determined three times (ε_1 , ε_2 , ε_3) both for each point of the measurement procedure and for each tested energy meter. This approach was aimed at ongoing control of the repeatability of the obtained measurement results.

Figures 6–8 show the errors of sample energy meters 1–3 obtained when the load currents are distorted by successive harmonics introduced selectively (100% of the base current I_b , $\cos\varphi = 1$).

Analyzing the graphs presented in Figures 6–11, it can be noticed that presence of a single harmonic in the load current does not cause significantly larger errors. Only in the case of the reactance nature of the load (100% of the base current I_b , $\cos\varphi = 0.5$), the errors are greater than permissible for the tested meters (class 1%), but they are similar regardless of which harmonic dominates in the load current distortion.

Figures 9–11 show the errors of sample energy meters 1–3 obtained when the load currents are distorted by successive harmonics introduced selectively (100% of the fundamental current I_b , $\cos\varphi = 0.5$).

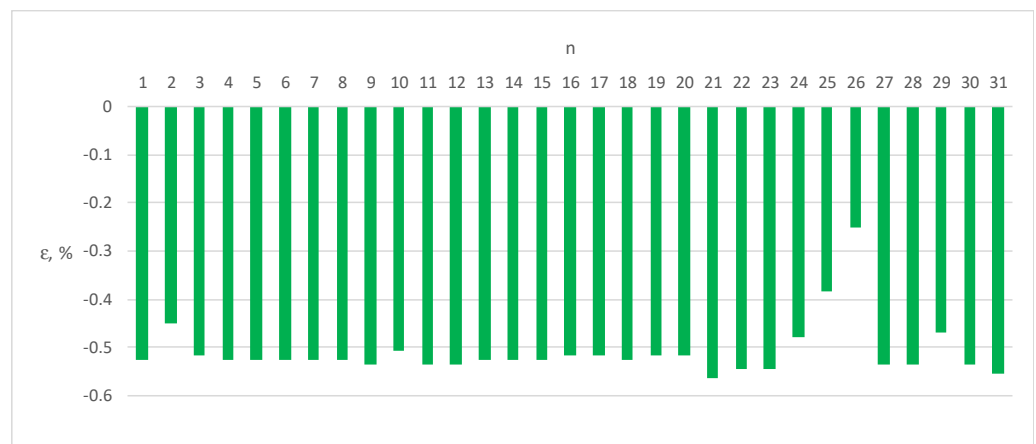


Figure 6. Errors ε of Energy Meter 1 for load current distorted by individual harmonics $n = 1\text{--}31$ (100% of the base current I_b , $\cos\varphi = 1$).

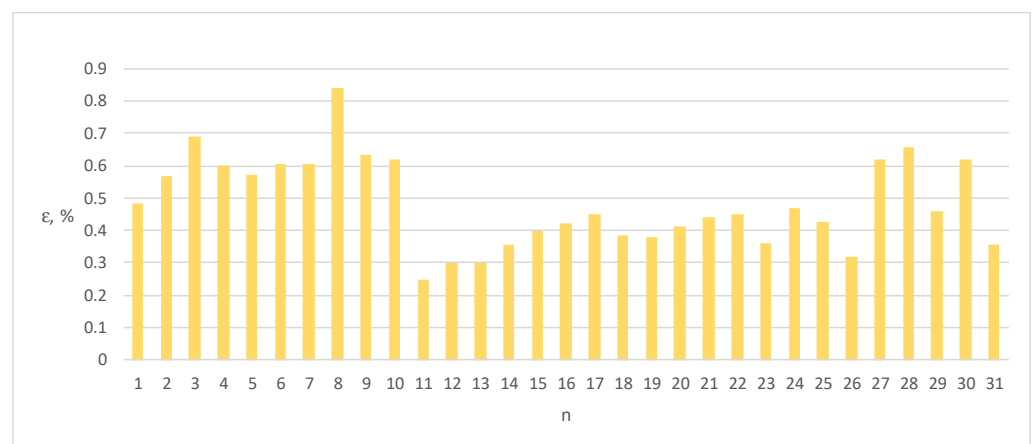


Figure 7. Errors ε of Energy Meter 2 for load current distorted by individual harmonics $n = 1\text{--}31$ (100% of the base current I_b , $\cos\varphi = 1$).

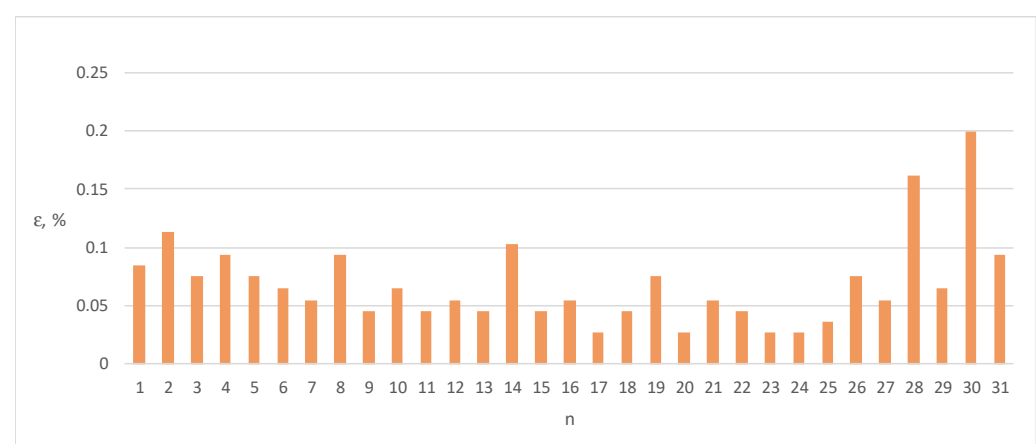


Figure 8. Errors ε of Energy Meter 3 for load current distorted by individual harmonics $n = 1\text{--}31$ (100% of the base current I_b , $\cos\varphi = 1$).

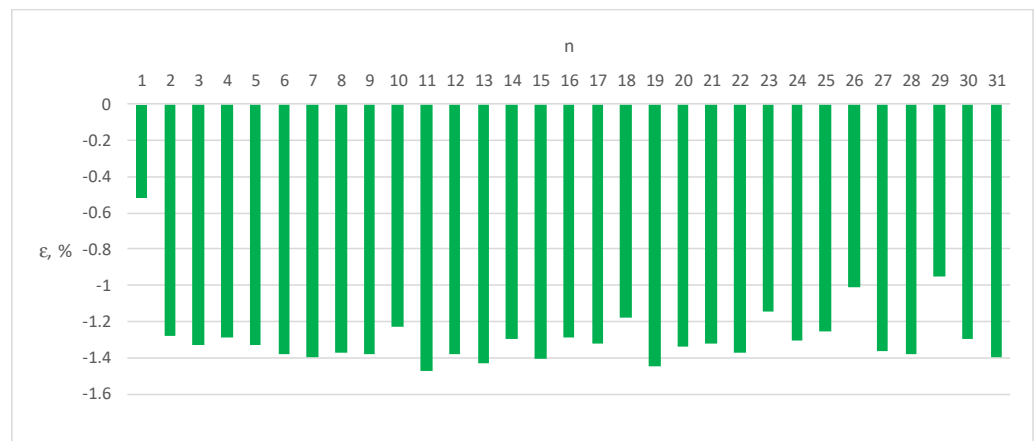


Figure 9. Errors ε of Energy Meter 1 for load current distorted by individual harmonics $n = 1\text{--}31$ (100% of the base current I_b , $\cos\varphi = 0.5$).

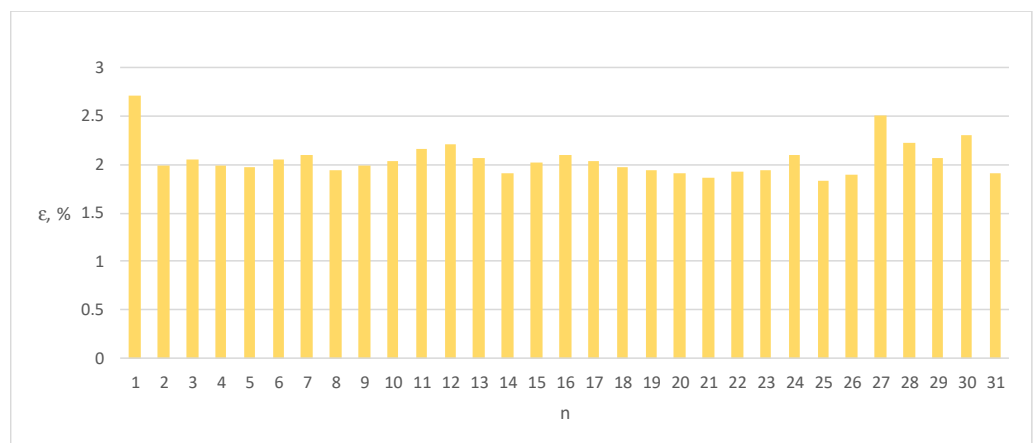


Figure 10. Errors ε of Energy Meter 2 for load current distorted by individual harmonics $n = 1\text{--}31$ (100% of the base current I_b , $\cos\varphi = 0.5$).

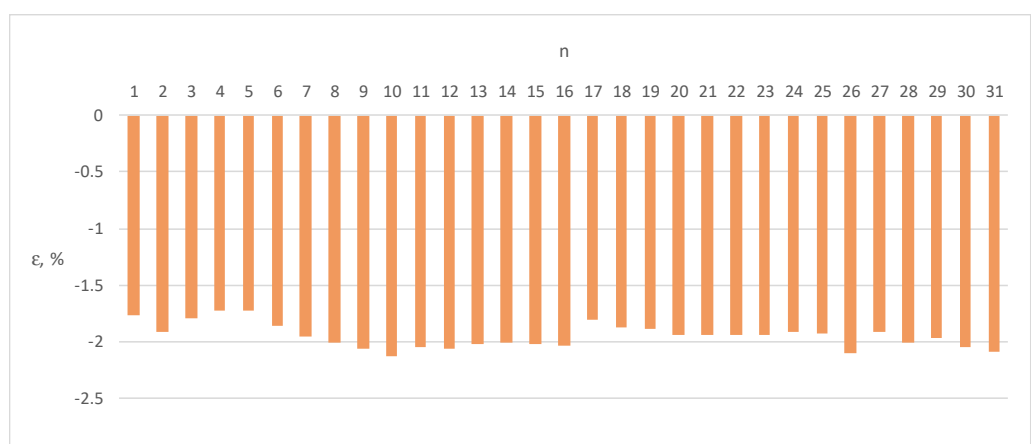


Figure 11. Errors ε of Energy Meter 3 for load current distorted by individual harmonics $n = 1\text{--}31$ (100% of the base current I_b , $\cos\varphi = 0.5$).

4.2. Method 2—Current Distortion Caused by the Sum of Subsequent Harmonics without Taking into Account Phase Shift

Method 2 involves distorting the load current of individual phases of the energy meter's current circuits by introducing multiple successive harmonics. In this method,

further harmonics are added to those previously introduced. This creates a waveform with increasing deformation and increasing THD. Subsequent odd harmonics are reduced in the range of 100–10% (by 6%), and all subsequent even harmonics are constant at 3% of the fundamental harmonic. This spectrum distribution is typical for non-linear receivers used in households. The purpose of such a measurement procedure was to check whether the tested sample meters are sensitive to distortions of variable magnitude.

Figure 12 shows the load current spectrum containing a sequence of 15 harmonics ($k = 15$) with decreasing content, as previously described.

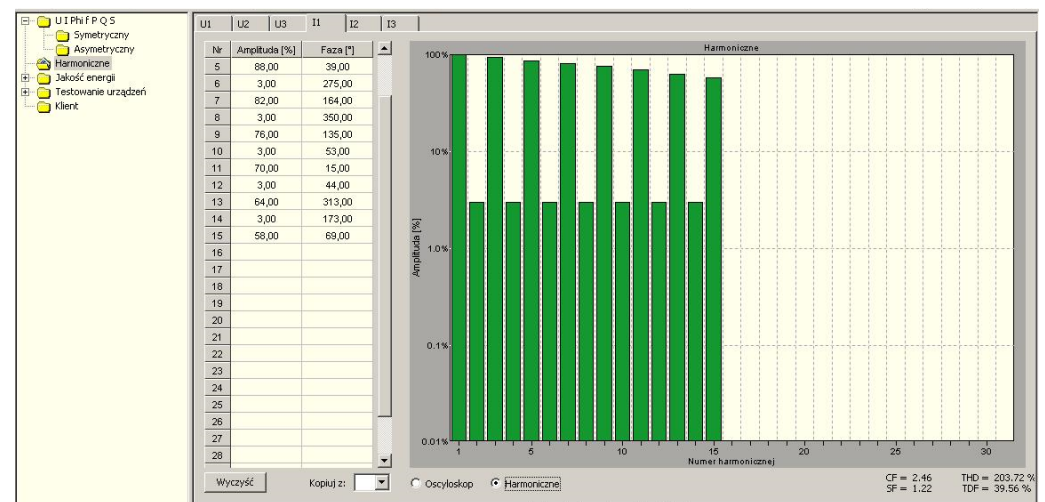


Figure 12. Screenshot of the CALPRO 300 shows load current spectrum containing a sequence of 15 harmonics ($k = 15$).

Tables 6–9 present the errors of energy meters obtained by distorting load currents with multiple successive harmonics, while maintaining the same points of the measurement procedure as in Method 1.

Table 6. Summary of energy meters errors for distorted load currents (100% 1st, 3% 2nd, 94% 3rd harmonic $k = 3$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\epsilon_1, \%$	$\epsilon_2, \%$	$\epsilon_3, \%$	$\epsilon_1, \%$	$\epsilon_2, \%$	$\epsilon_3, \%$	$\epsilon_1, \%$	$\epsilon_2, \%$	$\epsilon_3, \%$
0.1 $I_b, \cos \varphi = 1$	−0.583	−0.507	−0.545	0.547	0.547	0.547	0.296	0.296	0.296
1 $I_b, \cos \varphi = 1$	−0.498	−0.488	−0.488	0.301	0.301	0.306	0.084	0.075	0.113
1 $I_b, \cos \varphi = 0.5$	−2.806	−2.806	−2.801	2.009	1.937	1.932	−1.924	−1.873	−1.920
4 $I_b, \cos \varphi = 1$	−0.587	−0.665	−0.681	0.148	0.465	0.353	−0.580	−0.607	−0.556

Table 7. Summary of energy meters errors for distorted load currents (100% 1st, 3% 2nd, 94% 3rd, 3% 4th, 88% 5th harmonic $k = 5$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\epsilon_1, \%$	$\epsilon_2, \%$	$\epsilon_3, \%$	$\epsilon_1, \%$	$\epsilon_2, \%$	$\epsilon_3, \%$	$\epsilon_1, \%$	$\epsilon_2, \%$	$\epsilon_3, \%$
0.1 $I_b, \cos \varphi = 1$	−0.507	−0.545	−0.545	0.702	0.702	0.702	0.528	0.567	0.567
1 $I_b, \cos \varphi = 1$	−0.479	−0.488	−0.488	0.426	0.426	0.426	0.354	0.363	0.373
1 $I_b, \cos \varphi = 0.5$	−2.788	−2.842	−2.896	2.282	2.287	2.292	−1.549	−1.480	−1.549
4 $I_b, \cos \varphi = 1$	−0.693	−0.724	−0.684	0.288	0.258	0.268	−0.514	−0.563	−0.574

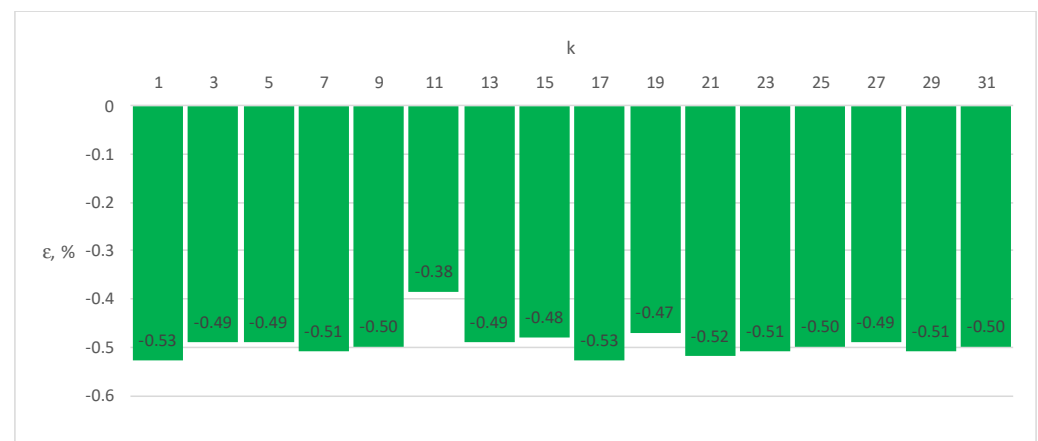
Table 8. Summary of energy meters errors for distorted load currents (100% 1st, 3% 2nd, 94% 3rd, 3% 4th, 88% 5th ... 3% 28th, 16% 29th harmonic $k = 29$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$
0.1 $I_b, \cos\varphi = 1$	−0.583	−0.545	−0.507	0.741	0.741	0.741	0.257	0.257	0.296
1 $I_b, \cos\varphi = 1$	−0.498	−0.507	−0.498	0.499	0.494	0.494	0.055	0.065	0.075
1 $I_b, \cos\varphi = 0.5$	−2.864	−2.855	−2.860	2.089	2.094	2.104	−2.090	−2.071	−2.071
4 $I_b, \cos\varphi = 1$	−0.670	−0.677	−0.663	0.289	0.267	0.260	−0.552	−0.616	−0.665

Table 9. Summary of energy meters errors for distorted load currents (100% 1st, 3% 2nd, 94% 3rd, 3% 4th, 88% 5th ... 3% 30th, 10% 31st harmonic $k = 31$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$
0.1 $I_b, \cos\varphi = 1$	−0.583	−0.545	−0.583	0.741	0.741	0.761	0.296	0.257	0.257
1 $I_b, \cos\varphi = 1$	−0.498	−0.498	−0.507	0.504	0.504	0.504	0.094	0.084	0.075
1 $I_b, \cos\varphi = 0.5$	−2.896	−2.892	−2.864	2.064	2.069	2.082	−1.878	−1.836	−1.892
4 $I_b, \cos\varphi = 1$	−0.658	−0.661	−0.668	0.292	0.268	0.255	−0.491	−0.550	−0.605

Figures 13–15 show the errors of sample energy meters 1–3 obtained when the load currents are distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ (100% of the base current $I_b, \cos\varphi = 1$).

**Figure 13.** Errors ε of Energy Meter 1 for load current distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ (100% of the base current $I_b, \cos\varphi = 1$).

Load current distortions caused by harmonic sequences $k = 3–31$ do not cause excessive errors in energy meters in most cases. Errors of tested meters did not exceed the permissible values (class 1%). Only in the case of the third energy meter, the errors for some sequences ($k = 3, k = 19$) were larger than for the remaining harmonic sequences.

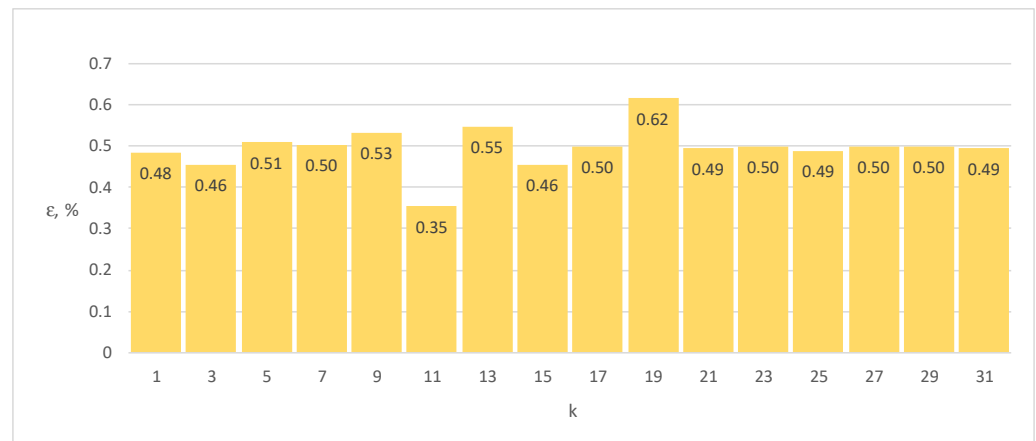


Figure 14. Errors ε of Energy Meter 2 for load current distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ (100% of the base current I_b , $\cos\varphi = 1$).

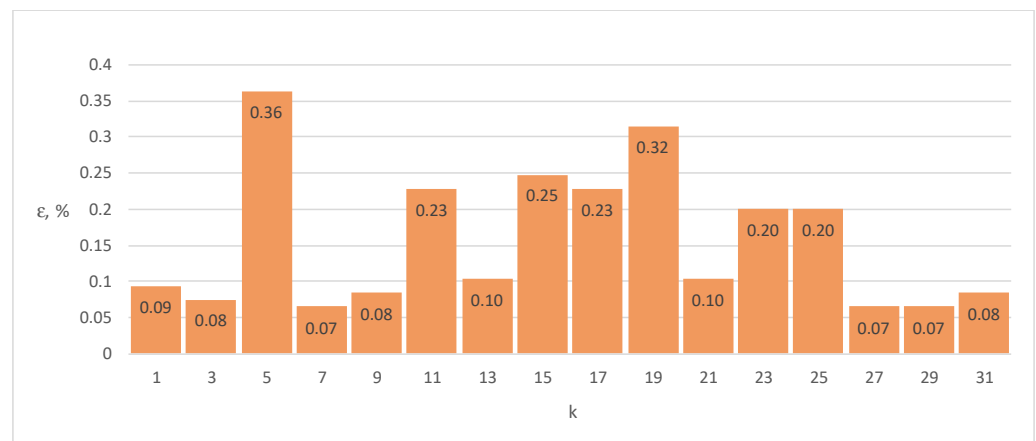


Figure 15. Errors ε of Energy Meter 3 for load current distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ (100% of the base current I_b , $\cos\varphi = 1$).

4.3. Method 3—Current Distortion Caused by the Sum of Subsequent Harmonics Taking into Account Phase Shifts

Method 3 involves distorting the load current of individual phases of the energy meter's current circuits again by introducing multiple successive harmonics. In this method, further harmonics are added to those previously introduced. This creates a waveform with increasing deformation and increasing THD. Subsequent odd harmonics were reduced in the range of 100–10% (by 6%), and all subsequent even harmonics are constant and amount to 3% of the fundamental harmonic. At the same time, during tests using this method, the phase shifts of individual harmonics were changed in order to increase the reality of the obtained distorted load current signals. The purpose of such a measurement procedure was to check whether the tested meter samples are sensitive to variable deformations and to variable phase shifts of individual harmonics. Tables 10–13 present the errors of energy meters obtained by distorting load currents with sequences of successive harmonics with different phase shifts while maintaining the same points of the measurement procedure as in Method 1.

Table 10. Summary of energy meters errors for distorted load currents with variable phase shifts of individual harmonics (100% 1st, 3% 2nd, 94% 3rd harmonic $k = 3$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$
0.1 $I_b, \cos \varphi = 1$	−0.583	−0.545	−0.583	0.858	0.858	0.858	0.296	0.257	0.296
1 $I_b, \cos \varphi = 1$	−0.526	−0.536	−0.536	0.620	0.620	0.615	0.248	0.190	0.209
1 $I_b, \cos \varphi = 0.5$	−1.247	−1.247	−1.242	2.237	2.212	2.217	−2.007	−1.943	−1.956
4 $I_b, \cos \varphi = 1$	−0.687	−0.697	−0.722	0.385	0.371	0.365	−0.567	−0.618	−0.569

Table 11. Summary of energy meters errors for distorted load currents with variable phase shifts of individual harmonics (100% 1st, 3% 2nd, 94% 3rd, 3% 4th, 88% 5th harmonic $n = 5$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$
0.1 $I_b, \cos \varphi = 1$	−0.545	−0.583	−0.583	0.839	0.839	0.839	0.412	0.450	0.450
1 $I_b, \cos \varphi = 1$	−0.517	−0.526	−0.526	0.600	0.605	0.600	0.094	0.132	0.094
1 $I_b, \cos \varphi = 0.5$	−1.176	−1.172	−1.158	2.217	2.214	2.222	−1.947	−1.979	−1.952
4 $I_b, \cos \varphi = 1$	−0.703	−0.679	−0.681	0.668	0.575	0.562	−0.469	−0.496	−0.599

Table 12. Summary of energy meters errors for distorted load currents with variable phase shifts of individual harmonics (100% 1st, 3% 2nd, 94% 3rd, 3% 4th, 88% 5th ... 3% 28th, 16% 29th harmonic $k = 29$).

	Energy Meter 1			Energy Meter 2			Energy Meter 3		
	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$
0.1 $I_b, \cos \varphi = 1$	0.450	0.489	0.412	0.839	0.858	0.858	0.334	0.296	0.296
1 $I_b, \cos \varphi = 1$	−0.279	−0.441	−0.441	0.615	0.615	0.610	0.075	0.084	0.084
1 $I_b, \cos \varphi = 0.5$	−1.345	−1.382	−1.456	2.134	2.134	2.144	−1.869	−1.883	−1.832
4 $I_b, \cos \varphi = 1$	−0.362	−0.673	−0.694	0.417	0.391	0.384	−0.630	−0.604	−0.537

Table 13. Summary of energy meters errors for distorted load currents with variable phase shifts of individual harmonics (100% 1st, 3% 2nd, 94% 3rd, 3% 4th, 88% 5th ... 3% 30th, 10% 31st harmonic $k = 31$).

	Energy meter 1			Energy meter 2			Energy meter 3		
	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$	$\varepsilon_1, \%$	$\varepsilon_2, \%$	$\varepsilon_3, \%$
0.1 $I_b, \cos \varphi = 1$	−0.583	−0.583	−0.583	0.702	0.702	0.702	0.334	0.296	0.334
1 $I_b, \cos \varphi = 1$	0.722	−0.431	−0.507	0.489	0.484	0.489	0.113	0.132	0.065
1 $I_b, \cos \varphi = 0.5$	−1.256	−1.251	−1.247	2.102	1.967	1.855	−1.855	−1.855	−1.827
4 $I_b, \cos \varphi = 1$	−0.177	−0.694	−0.169	0.354	0.399	0.369	−0.506	−0.461	−0.535

Figures 16–18 show the errors of sample energy meters 1–3 obtained when the load currents are distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ with variable phase shifts of individual harmonics (100% of the base current $I_b, \cos \varphi = 1$).

Taking into account phase shifts in harmonic sequences causing load current distortions did not result in a significant change in energy meters errors. Additionally, the research approach adopted in Method 3 did not show any clear relationship between energy meter errors and specific harmonic sequences causing distortions of the mentioned currents.

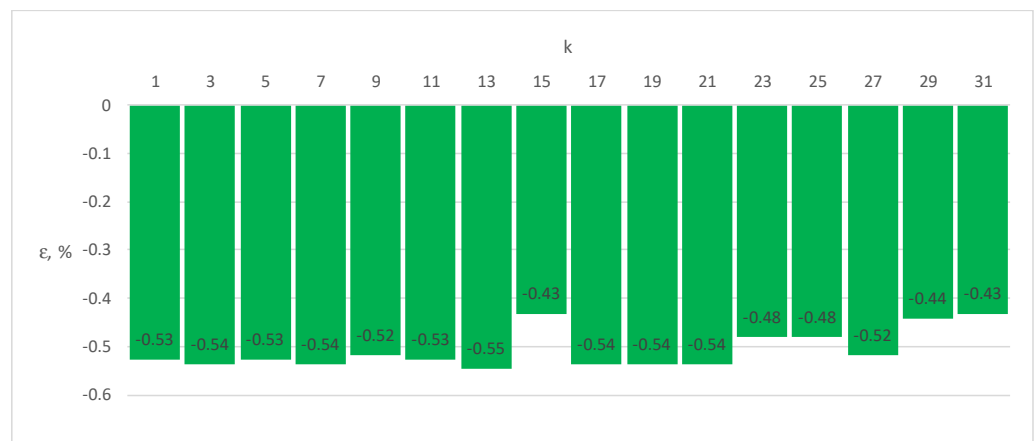


Figure 16. Errors ε of Energy Meter 1 for load current distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ with variable phase shifts of individual harmonics (100% of the base current I_b , $\cos\varphi = 1$).

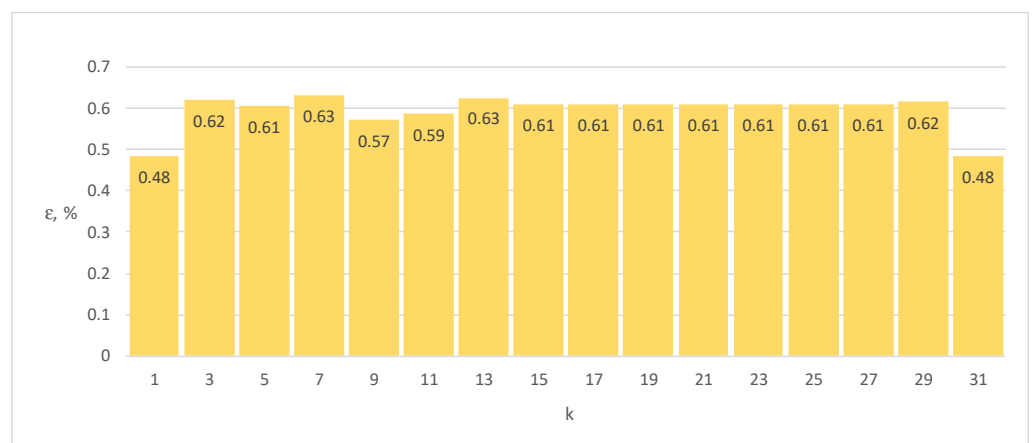


Figure 17. Errors ε of Energy Meter 2 for load current distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ with variable phase shifts of individual harmonics (100% of the base current I_b , $\cos\varphi = 1$).

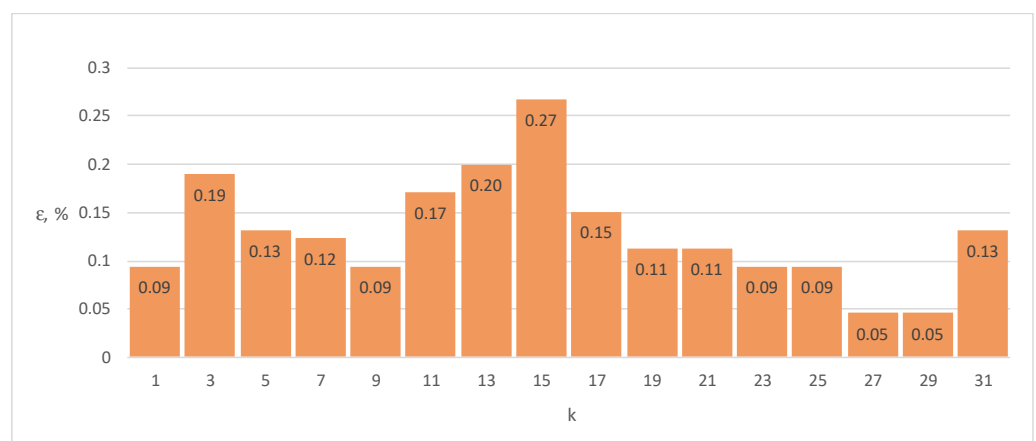


Figure 18. Errors ε of Energy Meter 3 for load current distorted by sequence of harmonics $k = 1, 3, 5, \dots, 31$ with variable phase shifts of individual harmonics (100% of the base current I_b , $\cos\varphi = 1$).

5. Conclusions

The CALPRO C300 calibrator works with software that allows you to set the distorted currents for the load by setting the magnitude and phase of each individual harmonic. This program also calculates the error of the tested meter using the power-time method,

taking the given calibrator settings as a reference point [32]. The errors of the tested energy meters presented in the article were determined in accordance with the current calibration procedure [33] both for sinusoidal alternating currents and for distorted currents containing up to 31 harmonics.

Both for the three example energy meters and for other tested devices, no significant exceeding of permissible errors were observed due to load current distortions either caused by selective harmonics or by harmonic sequences. However, exceeding of the permissible errors occurred in the case of the reactance nature of non-linear loads. This phenomenon, to a greater or lesser extent, concerned all meters tested, both used for billing and in building automation systems and photovoltaic installations.

Previously conducted research confirmed that for some non-linear loads the errors of energy meters exceed the permissible values. The suspicion that this may be caused by specific harmonics of the distorted current or sequences of these harmonics has not been confirmed by the research results presented in this article.

It is not possible to simulate all harmonic sequences in an unlimited quantitative dimension and for different phase shifts of subsequent harmonics. The tests performed only confirm that the tested energy meters turned out to be resistant to typical spectra of distorted load currents and did not show excessive measurement errors.

Continuation of similar research seems advisable in the face of widely used electronic energy meters, especially in billing and electricity distribution systems.

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