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MEASURING NONTECHNICAL POWER LOSSES USING MODERN DIAGNOSTIC TECHNIQUES

Abstract. *Measurement problems of non-technical losses of electricity related to energy flows and which are not controlled by metering and settlement systems are described. The paper presents the aspects of the theory about a cuboid of power with regard to the harmonic and distortion powers as well as about the working and reflected active powers as the basis for measuring losses. It was proposed to use the function of: power spectrum measurement, reflected active power measurement, harmonic and distortion power measurement, reference meter of working active power and cuboid of energy, implemented in Polish energy meters testers for non-technical losses measurement. The new measurement capabilities can be used to determine loss and balance sheet differences location as well as to limit energy losses in distribution. The theoretical considerations were supported by examples of the results of research on real power objects.*

Keywords: nontechnical losses, reflected active power, working active power, harmonic active power, measurement, harmonic.

Introduction

Electricity losses in the national power system are represented by the index of losses and balance sheet differences expressed by the following formula:

$$\Delta E_{\%} = \frac{\Delta E}{E_I} \cdot 100 \tag{1}$$

where:

ΔE - losses and balance sheet differences in the network,

E_I electricity introduced into the network.

In Poland, in recent years the value of the ΔE% indicator has a slightly decreasing tendency and remains at the level of about 1.5% in the HV network, 3.0% in the MV network and 5.7% in the LV network [1], which means that significant reserves in the field of energy efficiency improvement are in limiting losses, especially in low-voltage networks.

The balance sheet difference of the Distribution System Operator, as the difference between the energy introduced into the DSO network and the energy delivered from the DSO network results from losses:

- technical, related to energy flow through the network,
- non-technical, related with erroneous measurement results (errors of measuring and billing systems, measurement errors, inaccuracies and readings errors) and illegal consumption of electricity.

When considering non-technical losses related to erroneous measurement results, one should keep in mind the maxim of the Energy Manager [2]:

- You can’t manage what do don’t measure,
- If you don’t measure it, you can’t improve it.

Non-sinusoidal currents and voltages in power grids cause various problems, including non-technical losses of electricity [3,4]. These losses, in contrast to losses resulting from the illegal consumption of electricity, result from the imperfection of the measuring equipment used.

A cuboid of power and the theory of reflected power as the basis for measuring losses

In the analysis of non-technical energy losses, can be used the concepts of harmonic power *H* and distortion power *D* that occur in the apparent power equation *S* in the following form [5]:

$$S^2 = U^2 \cdot I^2 = S_1^2 + H^2 = P_1^2 + Q_1^2 + H^2 = P_1^2 + D^2 \tag{2}$$

where:
S_1 - first harmonic of apparent power,
P_1 first harmonic of active power,
Q_1 first harmonic of reactive power.

The harmonic power is given by the formula:

$$H = \sqrt{U^2 \sum_{n=2}^{\infty} I_n^2} \tag{3}$$

where:
n - harmonic order,
I_n - effective value of the n^th current harmonic.

The distortion power is given by the formula:

$$D = \sqrt{Q_1^2 + H^2} \tag{4}$$

A graphic representation of the defined powers is shown in the cuboid of power shown in Figure 1.

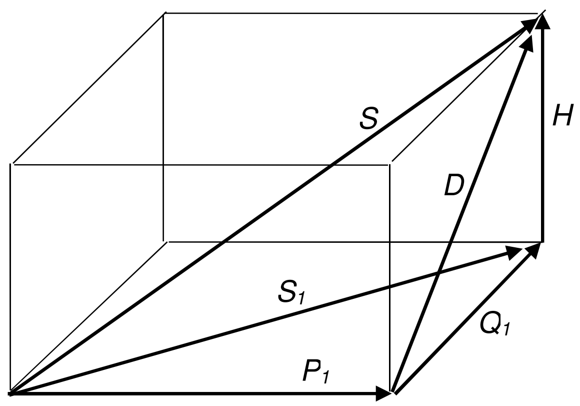

Fig.1. Cuboid of power

In the analysis of non-technical energy losses one can also use the concept of working active power and working energy proposed by prof. Czarnecki in [6], in which three components of active power were distinguished: working active power, reflected active power and detrimental active power. The active power *P* is given a formula

$$P = P_1 + \sum_{n=2}^{\infty} P_n = P_1 + P_h \tag{5}$$

where P_n are harmonics of power and P_h is the sum of harmonics of power. In the case of nonlinear receivers the P_h power has a negative value, it is the power of energy flow from the receiver to the source and for this reason it is called as the reflected active power P_r:

$$P_r = -P_h \tag{6}$$

The active power of the first harmonic P_1 is called the working active power and marked as P_w, hence the active power of the nonlinear receiver is given by the formula:

$$P = P_w - P_r \tag{7}$$

The theory of reflected active power has been confirmed experimentally. In laboratory tests of the real loads connected to a generator, it has been shown [7] that the percentage share of the reflected active power expressed as:

$$n/a = \frac{P_r}{P} \times 100\% = \frac{P_1 - P}{P} \times 100\% \tag{8}$$

provides up to several percent of active power. Whereas in the studies of the power consumed by the CNC machine tool, it has been shown [8] that the harmonics of power have a negative value, which confirms the correctness of the equation (6)

Power spectrum measurement function

The power spectrum measurement function consists in measuring the first harmonic of power P_1 and harmonics of power P_n with the visualization in the form of a histogram or table. Figure 2 shows an example of a histogram of active power harmonics of a real measuring laboratory supplied from a three-phase network. Harmonics with a positive sign are introduced by the supplier, while harmonics with a negative sign constitute the reflected active power.

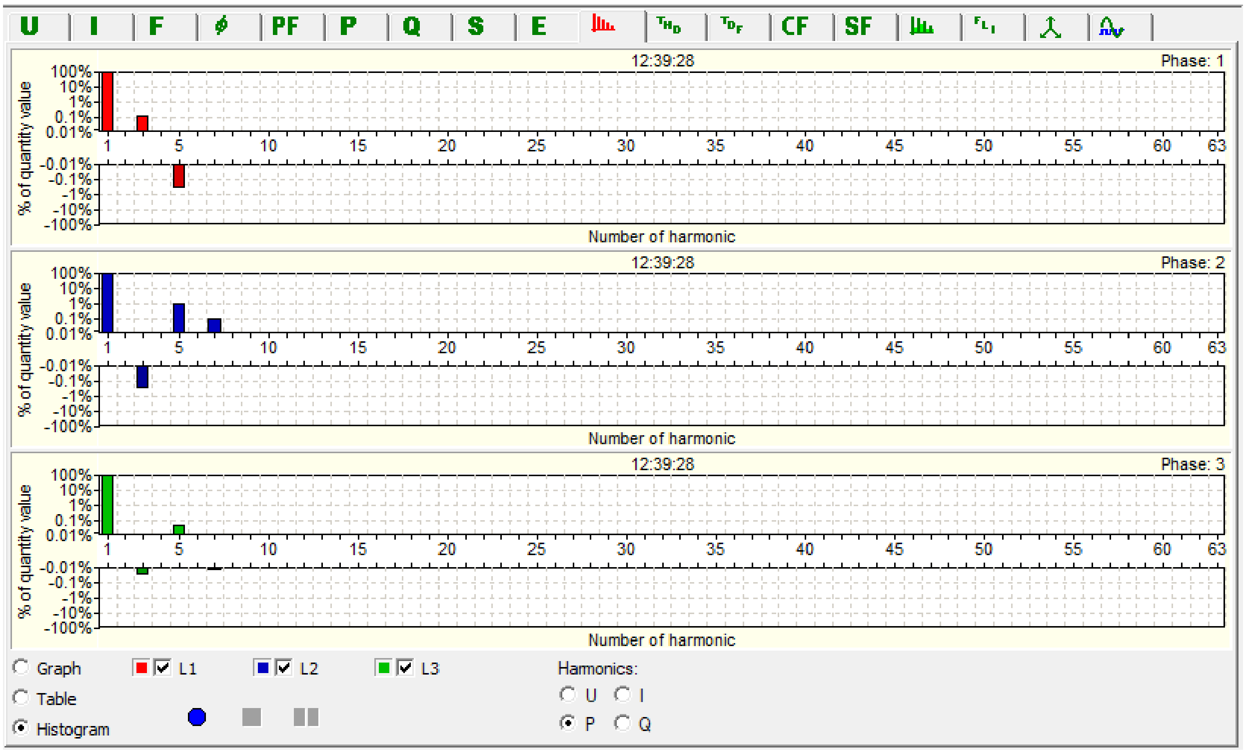

Fig.2. Histogram of harmonics of the active power of the measuring laboratory

The power harmonics histogram is a good tool for fast evaluation of the balance sheet difference in the power connection with separation into phase lines and individual harmonics. From the example Figure 2 it can be seen that in the L1 phase the reflected active power contained in the 5^{th} harmonic is greater than the active power of the 3^{rd} harmonic introduced by the DSO. Since the active energy meters measure power according to the formula (5), the counter readings are undervalued in the L1 phase. The reverse situation occurs in the L2 phase.

Modern testers of metering and billing systems have implemented the function of measuring the active and reactive power spectrum just for the purpose of studying the directions of energy flow. This functionality was already implemented in the Calport 100 tester, whose capabilities in this respect were presented in 2001 at the conference "Diagnostics in power grids at industrial plants" [9]. The histogram presented in Figure 2 has been measured by the latest Polish TE30 tester [10] .

Reflected active power measurement function

The function of measuring the reflected active power consists in measuring the active power P and the first harmonic of active power P_1, then from the formula (5) calculate the sum of harmonics of power P_h which according to the formula (7) is the reflected active power. Figure 3 shows an example of a table with active power and the first harmonics of active power a measurement laboratory supplied from a three-phase network, where P1, P2, P3 and PSum refer respectively to the active powers of L1, L2, L3 phases and their sum, while P1H1, P2H1, P3H1 and PSumH1 mean first harmonics of active powers of L1, L2, L3 phases and their sum.

For the line marked in Figure 3 from 16:47:30, the percentage share of the reflected active power, calculated from the formula (8), is +1.23% for the L1 phase, +0.21% for the L2 phase, +0.06% for the L3 phase and +0.21% for the sum of L123 phases. The reflected power measurement table is a good tool for the current evaluation of the share of reflected active power in individual phases.

Date	Time	P1	P2	P3	PSum	P1H1	P2H1	P3H1	PSumH1
2018-05-28	16:47:30	100.064 W	156.634 W	668.420 W	925.117 W	101.300 W	156.966 W	668.834 W	927.101 W
2018-05-28	16:47:31	99.5568 W	156.285 W	664.289 W	920.131 W	99.6194 W	157.809 W	664.267 W	921.696 W
2018-05-28	16:47:32	99.6631 W	156.699 W	664.628 W	920.991 W	100.363 W	158.351 W	665.587 W	924.301 W
2018-05-28	16:47:35	99.6556 W	155.428 W	666.392 W	921.475 W	100.837 W	157.079 W	668.509 W	926.425 W
2018-05-28	16:47:36	99.7051 W	156.670 W	674.177 W	930.552 W	100.053 W	158.458 W	672.615 W	931.126 W
2018-05-28	16:47:37	98.6814 W	156.269 W	666.732 W	921.683 W	100.773 W	157.880 W	667.017 W	925.670 W
2018-05-28	16:47:38	98.9097 W	156.967 W	668.073 W	923.949 W	98.6841 W	158.460 W	667.096 W	924.240 W
2018-05-28	16:47:39	101.699 W	156.031 W	666.650 W	924.379 W	102.135 W	157.993 W	665.742 W	925.870 W
2018-05-28	16:47:40	99.0662 W	155.740 W	667.077 W	921.883 W	99.8007 W	157.796 W	669.782 W	927.379 W
2018-05-28	16:47:41	99.0437 W	155.612 W	669.528 W	924.185 W	99.0104 W	157.571 W	668.849 W	925.430 W
2018-05-28	16:47:42	98.8668 W	156.120 W	665.625 W	920.613 W	99.1333 W	157.791 W	666.127 W	923.051 W
2018-05-28	16:47:43	98.5934 W	155.630 W	667.839 W	922.063 W	99.3996 W	157.522 W	670.405 W	927.327 W
2018-05-28	16:47:44	100.267 W	156.386 W	668.082 W	924.735 W	101.593 W	157.989 W	668.877 W	928.459 W
2018-05-28	16:47:45	99.7200 W	156.541 W	666.720 W	922.981 W	100.003 W	158.833 W	665.969 W	924.805 W
2018-05-28	16:47:46	99.1028 W	156.529 W	668.848 W	924.480 W	100.296 W	157.857 W	669.129 W	927.282 W
2018-05-28	16:47:47	98.8494 W	155.914 W	668.176 W	922.939 W	99.0346 W	157.733 W	666.574 W	923.342 W
2018-05-28	16:47:48	104.547 W	156.480 W	665.343 W	926.370 W	103.261 W	158.271 W	666.325 W	927.857 W

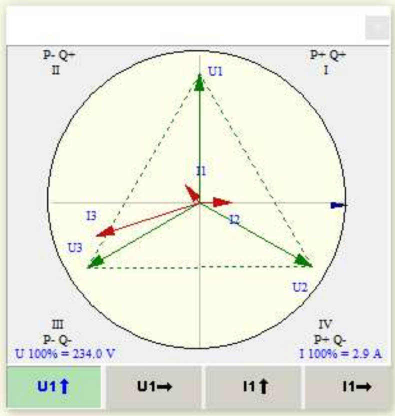

Fig.3. Table of active powers and first harmonic of active powers

Harmonic and distortion power measurement function

The function of measuring the distortion power D consists in measuring the apparent power S and the first harmonic of active power P_1 according to the following formula:

$$D = \sqrt{S^2 - P_1^2} \tag{9}$$

which results from the transformation of the formula (2). For this purpose, additional information about current values of apparent power is required, as shown in the table in Figure 4.

Date	Time	S1	S2	S3	SSum
2018-05-28	16:47:30	135.271 VA	206.236 VA	687.846 VA	1.02935 kVA
2018-05-28	16:47:31	134.619 VA	205.436 VA	684.026 VA	1.02408 kVA
2018-05-28	16:47:32	134.716 VA	205.663 VA	684.103 VA	1.02448 kVA
2018-05-28	16:47:35	134.839 VA	204.618 VA	686.596 VA	1.02605 kVA
2018-05-28	16:47:36	134.709 VA	205.694 VA	693.838 VA	1.03424 kVA
2018-05-28	16:47:37	133.691 VA	205.199 VA	686.992 VA	1.02588 kVA
2018-05-28	16:47:38	133.899 VA	205.593 VA	688.135 VA	1.02763 kVA
2018-05-28	16:47:39	136.511 VA	204.472 VA	686.773 VA	1.02776 kVA
2018-05-28	16:47:40	133.849 VA	204.429 VA	686.917 VA	1.02520 kVA
2018-05-28	16:47:41	133.774 VA	204.498 VA	689.531 VA	1.02780 kVA
2018-05-28	16:47:42	133.715 VA	205.235 VA	685.675 VA	1.02462 kVA
2018-05-28	16:47:43	133.550 VA	204.674 VA	687.947 VA	1.02617 kVA
2018-05-28	16:47:44	135.238 VA	205.455 VA	688.350 VA	1.02904 kVA
2018-05-28	16:47:45	134.817 VA	205.754 VA	686.907 VA	1.02748 kVA
2018-05-28	16:47:46	134.085 VA	205.682 VA	688.812 VA	1.02858 kVA
2018-05-28	16:47:47	133.811 VA	205.332 VA	688.109 VA	1.02725 kVA
2018-05-28	16:47:48	139.384 VA	205.445 VA	685.585 VA	1.03041 kVA

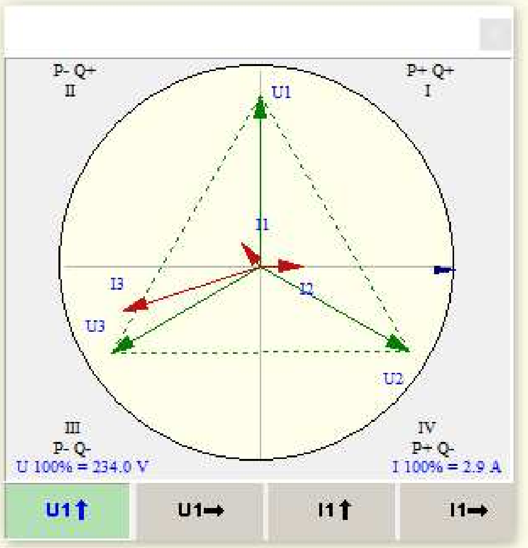

Fig.4. Table of apparent powers

The function of measuring the harmonic power *H* consists in measuring the apparent power *S* and the first harmonic of active power P_1 and also the first harmonic of reactive power Q_1 according to the following formula:

$$H = \sqrt{S^2 - P_1^2 - Q_1^2} \tag{10}$$

which results from the transformation of the formula (2). For this purpose, additional information about current values of first harmonic of reactive power is required, as shown in the table in Figure 5.

Date	Time	Q1	Q2	Q3	QSum	Q1H1	Q2H1	Q3H1	QSumH1
2018-05-28	16:47:30	-75.9295 Var	-88.4013 Var	142.846 Var	-21.4850 Var	-75.5730 Var	-89.3277 Var	143.315 Var	-21.5858 Var
2018-05-28	16:47:31	-75.8021 Var	-88.1333 Var	143.218 Var	-20.7177 Var	-75.9797 Var	-88.8213 Var	141.532 Var	-23.2687 Var
2018-05-28	16:47:32	-75.7912 Var	-88.3065 Var	141.138 Var	-22.9599 Var	-76.2428 Var	-89.1274 Var	142.748 Var	-22.6226 Var
2018-05-28	16:47:35	-75.6664 Var	-87.6389 Var	144.962 Var	-18.3429 Var	-75.5723 Var	-88.8799 Var	144.467 Var	-19.9854 Var
2018-05-28	16:47:36	-75.7344 Var	-87.9964 Var	143.417 Var	-20.3140 Var	-76.3648 Var	-88.8110 Var	144.119 Var	-21.0564 Var
2018-05-28	16:47:37	-75.3995 Var	-88.0508 Var	146.530 Var	-16.9207 Var	-75.1621 Var	-88.6640 Var	147.961 Var	-15.8651 Var
2018-05-28	16:47:38	-75.4043 Var	-87.9409 Var	144.488 Var	-18.8575 Var	-75.7639 Var	-89.1604 Var	144.115 Var	-20.8096 Var
2018-05-28	16:47:39	-75.8268 Var	-87.3020 Var	145.543 Var	-17.5856 Var	-76.4917 Var	-87.8937 Var	145.674 Var	-18.7114 Var
2018-05-28	16:47:40	-75.3455 Var	-87.3004 Var	143.439 Var	-19.2072 Var	-75.5760 Var	-87.9181 Var	145.779 Var	-17.7146 Var
2018-05-28	16:47:41	-75.2884 Var	-87.3671 Var	144.425 Var	-18.2303 Var	-75.2788 Var	-88.2934 Var	145.115 Var	-18.4571 Var
2018-05-28	16:47:42	-75.3485 Var	-87.6469 Var	143.268 Var	-19.7275 Var	-76.2169 Var	-88.0441 Var	143.916 Var	-20.3454 Var
2018-05-28	16:47:43	-75.3528 Var	-87.3586 Var	145.390 Var	-17.3219 Var	-75.3512 Var	-88.8641 Var	146.823 Var	-17.3918 Var
2018-05-28	16:47:44	-75.8110 Var	-87.5420 Var	145.557 Var	-17.7957 Var	-75.5673 Var	-88.5299 Var	146.193 Var	-17.9041 Var
2018-05-28	16:47:45	-75.6117 Var	-87.7789 Var	144.077 Var	-19.3141 Var	-76.1475 Var	-88.4893 Var	143.799 Var	-20.8376 Var
2018-05-28	16:47:46	-75.5261 Var	-87.8595 Var	144.545 Var	-18.8405 Var	-75.4324 Var	-88.3220 Var	144.313 Var	-19.4413 Var
2018-05-28	16:47:47	-75.6115 Var	-87.8956 Var	143.522 Var	-19.9850 Var	-75.9339 Var	-88.8373 Var	143.442 Var	-21.3295 Var
2018-05-28	16:47:48	-76.9646 Var	-87.6766 Var	145.271 Var	-19.3698 Var	-76.6186 Var	-88.3108 Var	145.290 Var	-19.6393 Var

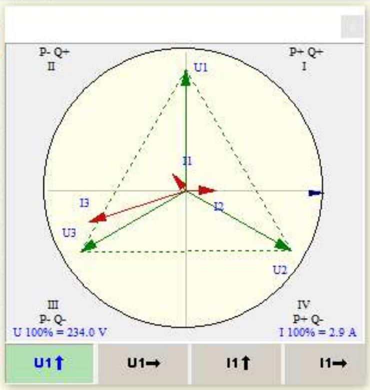

Fig.5. Table of reactive powers and first harmonic of reactive powers

Reference meter of working active power function

The reactive energy meters already measure reactive power and reactive energy from the components of currents and voltages of the fundamental frequency according to the standard EN 62053-24 [11]. In contrast, active energy meters, so far, measure the active power and active energy of all harmonics according to the standard EN 50470-3 [12]. This standard specifies the following conditions for testing an additional error due in the presence of harmonics in voltage and current:

- content of the 5th harmonic in voltage equal to 10% and in the current equal to 40%,
- fundamental frequency power factor equal to plus 1, which corresponds to the angle 0°,
- fundamental and 5th harmonic voltages are in phase,
- harmonic power factor equal to plus 1, which corresponds to the angle 0°.

A graphic illustration of these requirements is presented in Figure 6 in the form of print of the voltage and current oscilloscope screens and the histogram of the active power spectrum recorded with the TE30 tester cooperating with the C300B calibrator [13] as a signal source.

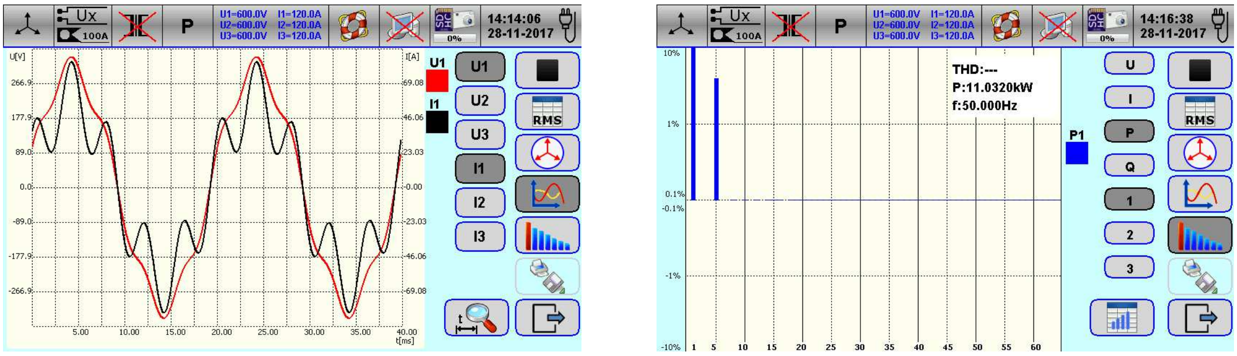

Fig.6. The voltage and current oscillogram and active power spectrum according to the requirements of the standard [12]

The conditions for testing an additional error due in the presence of harmonics, described in the standard [12], are unrepresentative of the conditions occurring in power grids with non-linear loads. At the peak of load current consumption, the voltage shape should be flattened and not raised up, as in the Figure 6. According to the theory of the working active power [6], the harmonic power of nonlinear receivers has a negative value, so the 5th harmonic power bar presented in Figure 6 should be down, not up from the zero line. Therefore, for further testing, the requirements of the standard [12] have been adjusted to the following:

- content of the 5th harmonic in voltage equal to 10% and in the current equal to 40%,
- fundamental frequency power factor equal to plus 1, which corresponds to the angle 0°,
- fundamental and 5th harmonic voltages are in reverse phase,
- harmonic power factor equal to minus1, which corresponds to the angle 180°.

The graphic illustration of the real requirements is shown in Figure 7 with the voltage shape flattened at the top and the 5th harmonic power bar with a negative value.

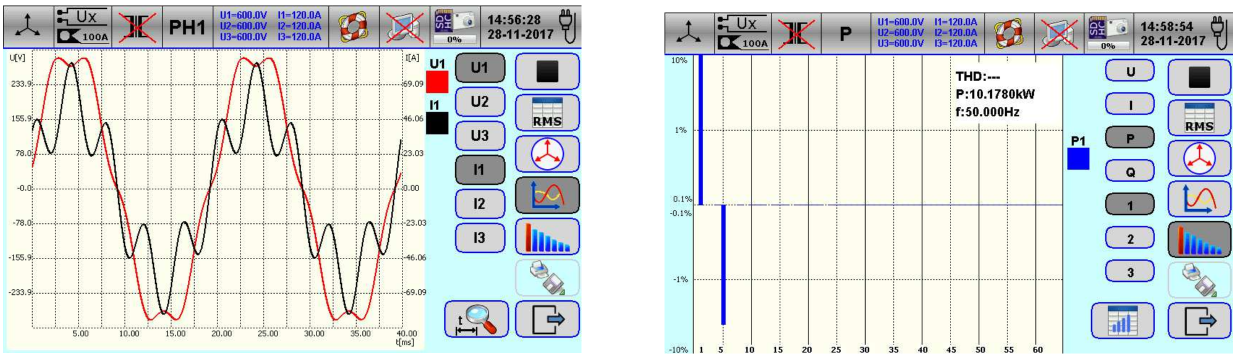

Fig.7. The voltage and current oscillogram and active power spectrum in accordance with the power theory [6]

In the conditions of presence of harmonics presented in Figure 7, an error test of a revenue energy meter was made using a reference meter in the following two modes:
- measuring the active power of all harmonics marked as P,
- measuring the first harmonic of power - working active power marked as PH1.

If the reference meter measures the active power of all harmonics, the revenue meter error is - 0.227% and it is within the accuracy class (Figure 8). If the reference meter measures the working active power, the revenue meter error is -4,217%. This negative error value means that the working active power flowing through the revenue meter is about 4% higher than the active power of the nonlinear receiver. The difference between the two results of the error measurement is not included in the settlement systems, it is a loss for the supplier and a bonus for the non-linear recipient.

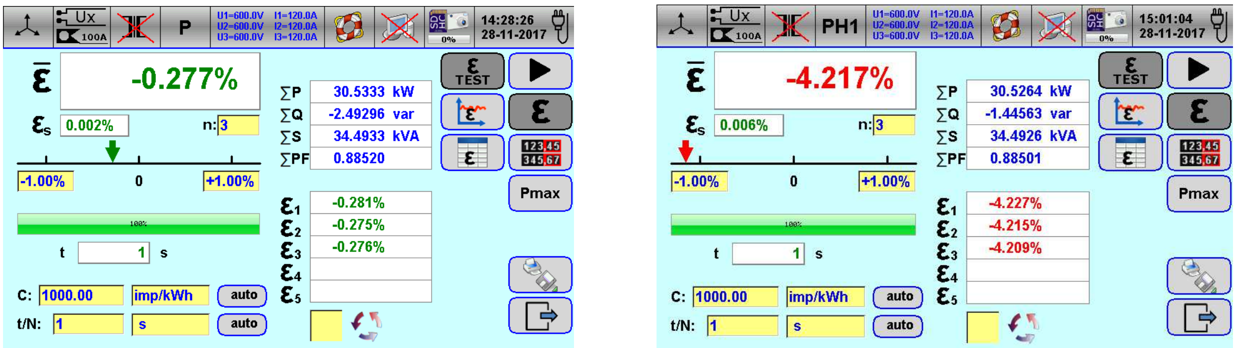

Fig.8. Measurement results of meter error at measuring of power P (left) and PH1 (right)

Cuboid of energy measurement function

Figure 9 presents a table with the results of measurement of the following energy components: active, reactive and apparent energy of L1, L2, L3 phases and their sum as well as first harmonics of active and reactive energy of L1, L2, L3 phases and their sum. It is the equivalent of an energy meter with twenty registers, whose indications can be refreshed every setting time - in an example table every 10 s. From the measurement results contained in the table you can calculate the reflected active energy, distortion energy and harmonic energy, changing in the previously described formulas (5), (9) and (10) powers for appropriate energies. The energy measurement function specified in the table Figure 9 enables the evaluation of non-technical losses in a given connection within a given time, eg a day with division into individual phases and determination of their occurrence time.

Date	Time	E PSum	E QSum	E SSum	E P1	E P2	E P3	E Q1	E Q2
2018-05-29	12:15:43	820.605 Wh	-92.4231 Varh	897.247 VAh	190.319 Wh	238.451 Wh	391.835 Wh	10.8461 Varh	-75.7707 Varh
2018-05-29	12:15:53	828.102 Wh	-93.2667 Varh	905.571 VAh	192.013 Wh	241.053 Wh	395.036 Wh	10.9528 Varh	-76.4770 Varh
2018-05-29	12:16:03	835.536 Wh	-94.1057 Varh	913.840 VAh	193.706 Wh	243.604 Wh	398.226 Wh	11.0494 Varh	-77.1696 Varh
2018-05-29	12:16:13	843.019 Wh	-94.9514 Varh	922.150 VAh	195.406 Wh	246.216 Wh	401.396 Wh	11.1589 Varh	-77.8802 Varh
2018-05-29	12:16:23	850.710 Wh	-95.8187 Varh	930.669 VAh	197.098 Wh	248.819 Wh	404.793 Wh	11.2630 Varh	-78.5877 Varh
2018-05-29	12:16:33	858.409 Wh	-96.6886 Varh	939.193 VAh	198.791 Wh	251.436 Wh	408.182 Wh	11.3682 Varh	-79.2966 Varh
2018-05-29	12:16:43	866.124 Wh	-97.5687 Varh	947.735 VAh	200.497 Wh	254.058 Wh	411.570 Wh	11.4694 Varh	-80.0082 Varh
2018-05-29	12:16:53	873.688 Wh	-98.4351 Varh	956.131 VAh	202.186 Wh	256.711 Wh	414.791 Wh	11.5711 Varh	-80.7261 Varh
2018-05-29	12:17:03	881.211 Wh	-99.2951 Varh	964.490 VAh	203.885 Wh	259.317 Wh	418.009 Wh	11.6718 Varh	-81.4380 Varh
2018-05-29	12:17:13	888.735 Wh	-100.153 Varh	972.846 VAh	205.575 Wh	261.937 Wh	421.223 Wh	11.7699 Varh	-82.1491 Varh
2018-05-29	12:17:23	896.228 Wh	-101.014 Varh	981.158 VAh	207.268 Wh	264.535 Wh	424.426 Wh	11.8671 Varh	-82.8494 Varh
2018-05-29	12:17:33	903.771 Wh	-101.872 Varh	989.511 VAh	208.962 Wh	267.183 Wh	427.625 Wh	11.9661 Varh	-83.5576 Varh
2018-05-29	12:17:43	911.292 Wh	-102.731 Varh	997.853 VAh	210.651 Wh	269.789 Wh	430.852 Wh	12.0664 Varh	-84.2659 Varh
2018-05-29	12:17:53	918.728 Wh	-103.583 Varh	1.00610 kVAh	212.345 Wh	272.393 Wh	433.990 Wh	12.1681 Varh	-84.9759 Varh
2018-05-29	12:18:03	926.248 Wh	-104.445 Varh	1.01443 kVAh	214.034 Wh	275.008 Wh	437.206 Wh	12.2575 Varh	-85.6813 Varh
2018-05-29	12:18:13	933.722 Wh	-105.278 Varh	1.02274 kVAh	215.731 Wh	277.549 Wh	440.443 Wh	12.3605 Varh	-86.3764 Varh
2018-05-29	12:18:23	941.154 Wh	-106.117 Varh	1.03100 kVAh	217.427 Wh	280.087 Wh	443.640 Wh	12.4630 Varh	-87.0647 Varh
2018-05-29	12:18:33	949.160 Wh	-107.013 Varh	1.03982 kVAh	219.116 Wh	282.680 Wh	447.364 Wh	12.5646 Varh	-87.7670 Varh
2018-05-29	12:18:43	957.080 Wh	-107.897 Varh	1.04857 kVAh	220.787 Wh	285.232 Wh	451.061 Wh	12.6796 Varh	-88.4661 Varh
2018-05-29	12:18:53	965.105 Wh	-108.790 Varh	1.05740 kVAh	222.458 Wh	287.853 Wh	454.795 Wh	12.7800 Varh	-89.1670 Varh
2018-05-29	12:19:03	972.673 Wh	-109.639 Varh	1.06578 kVAh	224.125 Wh	290.427 Wh	458.122 Wh	12.8890 Varh	-89.8620 Varh
2018-05-29	12:19:13	980.268 Wh	-110.497 Varh	1.07419 kVAh	225.794 Wh	293.035 Wh	461.439 Wh	12.9996 Varh	-90.5679 Varh
2018-05-29	12:19:23	987.923 Wh	-111.398 Varh	1.08268 kVAh	227.459 Wh	295.695 Wh	464.769 Wh	13.1079 Varh	-91.3072 Varh
2018-05-29	12:19:33	995.490 Wh	-112.253 Varh	1.09108 kVAh	229.129 Wh	298.284 Wh	468.076 Wh	13.2204 Varh	-92.0128 Varh
2018-05-29	12:19:43	1.00312 kWh	-113.120 Varh	1.09954 kVAh	230.798 Wh	300.925 Wh	471.400 Wh	13.3315 Varh	-92.7316 Varh
2018-05-29	12:19:53	1.01078 kWh	-114.006 Varh	1.10802 kVAh	232.458 Wh	303.586 Wh	474.734 Wh	13.4335 Varh	-93.4519 Varh
2018-05-29	12:20:03	1.01820 kWh	-114.855 Varh	1.11627 kVAh	234.131 Wh	306.190 Wh	477.882 Wh	13.5501 Varh	-94.1681 Varh
2018-05-29	12:20:13	1.02588 kWh	-115.870 Varh	1.12481 kVAh	235.798 Wh	308.878 Wh	481.207 Wh	13.6647 Varh	-95.0285 Varh
2018-05-29	12:20:23	1.03347 kWh	-116.726 Varh	1.13323 kVAh	237.471 Wh	311.464 Wh	484.537 Wh	13.7773 Varh	-95.7347 Varh
2018-05-29	12:20:33	1.04095 kWh	-117.598 Varh	1.14152 kVAh	239.141 Wh	314.096 Wh	487.713 Wh	13.8913 Varh	-96.4514 Varh
2018-05-29	12:20:43	1.04833 kWh	-118.439 Varh	1.14972 kVAh	240.810 Wh	316.710 Wh	490.809 Wh	14.0042 Varh	-97.1631 Varh

Date	Time	E Q3	E S1	E S2	E S3	E P1H1	E P2H1	E P3H1	E PSumH1	E Q1H1	E Q2H
2018-05-29	12:15:43	-27.4984 Varh	198.912 VAh	298.760 VAh	399.575 VAh	191.106 Wh	241.782 Wh	391.962 Wh	824.851 Wh	10.5784 Varh	-75.9625
2018-05-29	12:15:53	-27.7426 Varh	200.688 VAh	302.036 VAh	402.847 VAh	192.816 Wh	244.416 Wh	395.148 Wh	832.381 Wh	10.6863 Varh	-76.6747
2018-05-29	12:16:03	-27.9855 Varh	202.462 VAh	305.269 VAh	406.110 VAh	194.509 Wh	247.002 Wh	398.346 Wh	839.857 Wh	10.7776 Varh	-77.3718
2018-05-29	12:16:13	-28.2301 Varh	204.243 VAh	308.556 VAh	409.352 VAh	196.217 Wh	249.648 Wh	401.518 Wh	847.383 Wh	10.8851 Varh	-78.0854
2018-05-29	12:16:23	-28.4940 Varh	206.015 VAh	311.833 VAh	412.822 VAh	197.919 Wh	252.287 Wh	404.918 Wh	855.124 Wh	10.9864 Varh	-78.7978
2018-05-29	12:16:33	-28.7602 Varh	207.789 VAh	315.120 VAh	416.285 VAh	199.622 Wh	254.935 Wh	408.307 Wh	862.864 Wh	11.0910 Varh	-79.5136
2018-05-29	12:16:43	-29.0299 Varh	209.575 VAh	318.417 VAh	419.743 VAh	201.336 Wh	257.587 Wh	411.691 Wh	870.615 Wh	11.1878 Varh	-80.2283
2018-05-29	12:16:53	-29.2800 Varh	211.344 VAh	321.750 VAh	423.038 VAh	203.033 Wh	260.276 Wh	414.914 Wh	878.223 Wh	11.2872 Varh	-80.9532
2018-05-29	12:17:03	-29.5289 Varh	213.123 VAh	325.040 VAh	426.328 VAh	204.740 Wh	262.915 Wh	418.146 Wh	885.800 Wh	11.3841 Varh	-81.6701
2018-05-29	12:17:13	-29.7740 Varh	214.893 VAh	328.338 VAh	429.615 VAh	206.440 Wh	265.572 Wh	421.357 Wh	893.369 Wh	11.4784 Varh	-82.3869
2018-05-29	12:17:23	-30.0320 Varh	216.665 VAh	331.603 VAh	432.890 VAh	208.138 Wh	268.198 Wh	424.550 Wh	900.887 Wh	11.5744 Varh	-83.0926
2018-05-29	12:17:33	-30.2809 Varh	218.440 VAh	334.909 VAh	436.162 VAh	209.839 Wh	270.881 Wh	427.761 Wh	908.481 Wh	11.6691 Varh	-83.8050
2018-05-29	12:17:43	-30.5314 Varh	220.209 VAh	338.182 VAh	439.462 VAh	211.537 Wh	273.516 Wh	430.984 Wh	916.036 Wh	11.7661 Varh	-84.5152
2018-05-29	12:17:53	-30.7751 Varh	221.983 VAh	341.448 VAh	442.669 VAh	213.236 Wh	276.154 Wh	434.132 Wh	923.522 Wh	11.8653 Varh	-85.2284
2018-05-29	12:18:03	-31.0208 Varh	223.752 VAh	344.724 VAh	445.956 VAh	214.934 Wh	278.802 Wh	437.346 Wh	931.083 Wh	11.9538 Varh	-85.9369
2018-05-29	12:18:13	-31.2624 Varh	225.529 VAh	347.941 VAh	449.266 VAh	216.637 Wh	281.371 Wh	440.583 Wh	938.591 Wh	12.0569 Varh	-86.6374
2018-05-29	12:18:23	-31.5155 Varh	227.305 VAh	351.158 VAh	452.534 VAh	218.338 Wh	283.935 Wh	443.779 Wh	946.052 Wh	12.1530 Varh	-87.3297
2018-05-29	12:18:33	-31.8104 Varh	229.074 VAh	354.417 VAh	456.329 VAh	220.036 Wh	286.554 Wh	447.505 Wh	954.095 Wh	12.2543 Varh	-88.0395
2018-05-29	12:18:43	-32.1102 Varh	230.821 VAh	357.651 VAh	460.097 VAh	221.712 Wh	289.137 Wh	451.214 Wh	962.064 Wh	12.3647 Varh	-88.7441
2018-05-29	12:18:53	-32.4029 Varh	232.565 VAh	360.934 VAh	463.903 VAh	223.391 Wh	291.786 Wh	454.942 Wh	970.119 Wh	12.4661 Varh	-89.4511
2018-05-29	12:19:03	-32.6663 Varh	234.307 VAh	364.174 VAh	467.302 VAh	225.061 Wh	294.390 Wh	458.270 Wh	977.721 Wh	12.5709 Varh	-90.1477
2018-05-29	12:19:13	-32.9283 Varh	236.051 VAh	367.448 VAh	470.693 VAh	226.736 Wh	297.034 Wh	461.597 Wh	985.367 Wh	12.6806 Varh	-90.8583
2018-05-29	12:19:23	-33.1983 Varh	237.791 VAh	370.795 VAh	474.096 VAh	228.411 Wh	299.688 Wh	464.927 Wh	993.025 Wh	12.7869 Varh	-91.5840
2018-05-29	12:19:33	-33.4609 Varh	239.537 VAh	374.067 VAh	477.475 VAh	230.085 Wh	302.310 Wh	468.223 Wh	1.00062 kWh	12.8970 Varh	-92.2947
2018-05-29	12:19:43	-33.7196 Varh	241.282 VAh	377.388 VAh	480.871 VAh	231.764 Wh	304.987 Wh	471.548 Wh	1.00830 kWh	13.0075 Varh	-93.0248
2018-05-29	12:19:53	-33.9877 Varh	243.016 VAh	380.729 VAh	484.277 VAh	233.429 Wh	307.677 Wh	474.884 Wh	1.01599 kWh	13.1060 Varh	-93.7511
2018-05-29	12:20:03	-34.2366 Varh	244.765 VAh	384.015 VAh	487.494 VAh	235.110 Wh	310.314 Wh	478.039 Wh	1.02346 kWh	13.2194 Varh	-94.4729
2018-05-29	12:20:13	-34.5060 Varh	246.507 VAh	387.405 VAh	490.894 VAh	236.784 Wh	313.037 Wh	481.360 Wh	1.03118 kWh	13.3309 Varh	-95.3352
2018-05-29	12:20:23	-34.7681 Varh	248.255 VAh	390.674 VAh	494.296 VAh	238.462 Wh	315.647 Wh	484.698 Wh	1.03881 kWh	13.4410 Varh	-96.0478
2018-05-29	12:20:33	-35.0374 Varh	249.999 VAh	393.978 VAh	497.544 VAh	240.141 Wh	318.317 Wh	487.884 Wh	1.04634 kWh	13.5528 Varh	-96.7694
2018-05-29	12:20:43	-35.2804 Varh	251.744 VAh	397.270 VAh	500.707 VAh	241.811 Wh	320.958 Wh	490.982 Wh	1.05375 kWh	13.6612 Varh	-97.4856

Graph / Table — Averaging every 10 results

Fig.9. The table of energy measurement results

From the measurement results of energy components listed in the table, one can, in analogy to the cuboid of power presented in Figure 1, present a graphical representation of the measured energy in the form of energy cuboids for each phase and their sum.

Conclusion

To be able to improve energy efficiency by limiting non-technical losses, tools for measuring the energy flow are needed. Non-sinusoidal currents and voltages in power grids cause energy flows in different directions, while the flow of part of the energy is not controlled due to imperfections of the measuring equipment.

Energy flows and losses can be analyzed using the power cuboid theory or the theory of reflected active power. The theory of reflected active power, developed by prof. Czarnecki, is particularly interesting for the measurement of losses, because the reflected active power is a pure loss. It was only proven two years ago, in the work [7] carried out in the USA, that the fundamental theses of this theory on the flow of harmonic energy in the opposite direction to the first harmonic energy flow were experimentally confirmed in the laboratory stand.

In Poland, we have a particularly favorable situation with regard to the capacity to measure losses related to energy flows that have not been controlled until now. The national meter tester type TE30 [1] and the three-phase system with a reference meter and an integrated three-phase source type TS33 [14] have dedicated functions for the measurement of losses. Power measurement functions such as power spectrum, reflected active power, distortion power or harmonic power enable current evaluation of energy flows that are variable over time. The function of reference meter of working active power enables the measurement of the percentage error in calculating energy due to uncontrolled energy flows through the installed metering and billing system. The cuboid of energy function enables the measurement of all energy components to accurately calculate losses.

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