IEEE CANDO EPE 2020

3rd International IEEE Conference AND workshop in Óbuda on Electrical and Power Engineering

Energy Efficiency versus Harmonic Analysis in Low Voltage Networks

Mircea Buzdugan
Călin Ciugudeanu
Angel Câmpianu

Technical University of Cluj-Napoca, Romania

November 18-19, 2020

Outline:

I. INTRODUCTION

In the introductory section, a few aspects related to the motivation of the increasingly concern for power quality issues are presented.

- The intensive use of a new generation of equipment, controlled by microprocessors and power electronics devices, more sensitive to electric power quality events. However, nowadays producers are seeking to manufacture more robust equipment in terms of power quality and electromagnetic compatibility as well.
- The emphasis placed recently on energy efficiency, in the context of the continuous increase of adjustable/variable speed electric drives.
- The harmonic content and the precarious power factor that accompany these applications which require necessarily certain countermeasures to increase energy efficiency.
- End users are more careful regarding power quality issues, consequently putting a permanent pressure on utility providers, especially in the context of the deregulated electricity market.
- Distributed generation and renewable energy sources create new challenges for power quality, most interfaces with renewable energy sources being sensitive to voltage disturbances, mainly to temporary voltage drops.
- Finally, due to the interconnection, inherent to almost all electric grids, the occurrence of power quality problems at the local level of an end-user, can cause their spread to neighboring users, thus affecting the proper operation of an extended part of the grid or even worse, damaging equipment connected thereto.

II. From the Earliest Concern on Power Quality up to the Standard IEEE Std. 1459-2010

The main problem stems from the flow of nonactive energy caused by harmonic currents and voltages. There is a need to quantify correctly the distortions caused by the nonlinear and parametric loads, and to apply a fair distribution of the financial burden required to maintain the quality of electric service.

The theory of power is a collective product which determined plenty of power definitions and aroused lively debates that last from more than a century.

All started from one question, namely why a load with the active power *P* usually demands a power source with greater apparent power *S*. Invoking Schwarz's inequality:

$$P^2 = \left[\frac{1}{T}\int_0^T v(t)\cdot i(t)\cdot dt\right]^2 \le \left[\frac{1}{T}\int_0^T v(t)^2\, dt\right]\cdot\left[\frac{1}{T}\int_0^T i(t)^2\, dt\right] = V^2\cdot I^2 = S^2$$

It results that: $\boldsymbol{S^2 = P^2 + N^2}$ where $\boldsymbol{N}$ is the total **nonactive** or **fictitious power.**

In 1927, C. I. Budeanu developed its theory about electric powers, based on the decomposition of the voltage and the current in harmonic components.

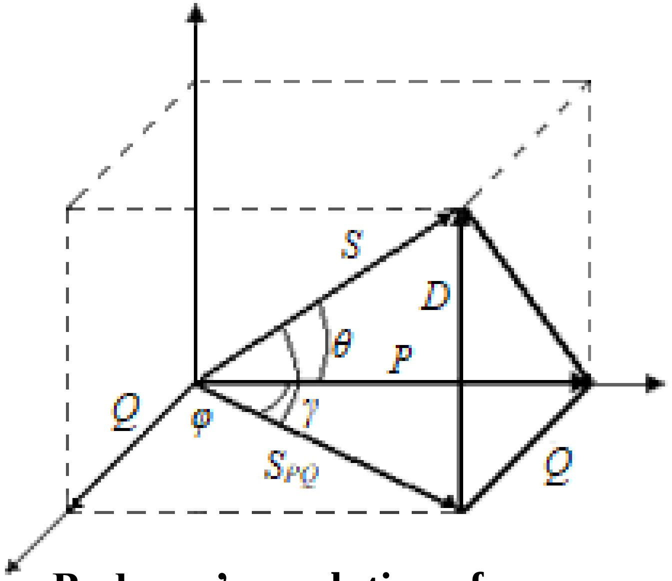
$$S^2 = V^2 I^2 = \left(\sum_{h=0}^{h_{\max}} \left(V_h I_h \cos\varphi_h \right) \right)^2 + \left(\sum_{h=0}^{h_{\max}} \left(V_h I_h \sin\varphi_h \right) \right)^2 + \sum_{h=0}^{h_{\max}-1} \sum_{i=h+1}^{h_{\max}} \left[\left(V_h I_i \right)^2 + \left(V_i I_h \right)^2 - 2 V_h V_i I_h I_i \cos\left(\varphi_h - \varphi_i \right) \right]$$

The equation $\boldsymbol{S^2 = P^2 + N^2}$ became in Budeanu's theory: $\boldsymbol{S^2 = P^2 + Q^2 + D^2}$, that defines a tetrahedron. Following this resolution, three factors arouse:

- the power factor: $PF = \cos\theta = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}}$

- the displacement power factor: $\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}}$

- the distortion power factor: $\cos\gamma = \frac{\left| S_{PQ} \right|}{S}$



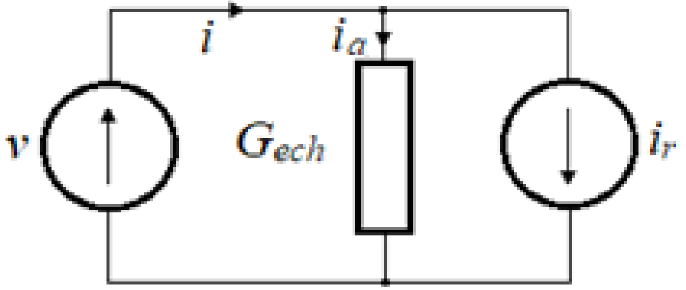
Budeanu's resolution of powers

The three factors above are related by the equation: $PF = \cos\theta = \frac{P}{S} = \cos\varphi \cdot \cos\gamma$

Fryze's Definition

Fryze developed his theory **in the time domain**, based on the physical decomposition of the current into two components, the **active**, respectively the **residual** one

$$i(t) = i_a(t) + i_r(t)$$

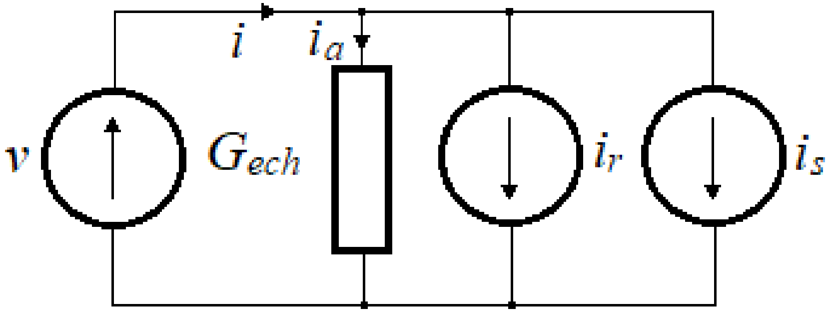


Fryze's equivalent circuit

The biggest error of interpretation of Fryze consists in the rejection of the concepts of harmonics, but Fryze's theory has the merit that it represented the base of further developments, especially Czarnecki's theory.

Czarnecki's Definition

Czarnecki introduces the so-called **currents' physical components** (CPC). Besides the equivalent conductance of the load, one can notice two current sources: i_r, **the instantaneous reactive current** and i_s, **the instantaneous scattered current**.



Czarnecki's equivalent circuit

In literature one can find also, other definitions belonging to **Sheperd** and **Zakikhani**, **Sharon**, **Depenbrock**, **Emanuel**, etc.

IEEE Std. 1459-2010 Definition

The philosophy of the IEEE Std. 1459-2010 is to separate P_1 and Q_1 from the rest of the powers. Consequently, the fundamental components of the voltage and the current will be separated from the rest of the components.

$$V^2 = V_1^2 + V_H^2,\ V_H^2 = \sum_{h \neq 1} V_h^2;\ I^2 = I_1^2 + I_H^2,\quad I_H^2 = \sum_{h \neq 1} I_h^2 \longrightarrow THD_V = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1};\quad THD_I = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1}.$$

The active power (Watt) is divided into two components:

$$P = P_1 + P_H \begin{cases} P_1 = V_1 I_1 \cos\theta_1 \\ P_H = V_0 I_0 + \sum_{h \neq 1} V_h I_h \cos\theta_h = P - P_1 \end{cases}$$

Note that ***h*** is not necessarily an integer.

The fundamental reactive power (var) is: $Q_1 = V_1 I_1 \sin\theta_1$

The fundamental apparent power (VA) is: $S_1 = V_1 I_1 = \sqrt{P_1^2 + Q_1^2}$

The apparent power (VA) is resolved in the following manner:

$$S^2 = \left(V_1^2 + V_H^2\right)\left(I_1^2 + I_H^2\right) = \left(V_1 I_1\right)^2 + \left(V_1 I_H\right)^2 + \left(V_H I_1\right)^2 + \left(V_H I_H\right)^2 = S_1^2 + S_N^2$$

where $\boldsymbol{S_N}$ is the **nonfundamental apparent power**.

S_N, the nonfundamental apparent power is resolved in the following three distinctive terms: $S_N^2 = D_I^2 + D_V^2 + S_H^2$

a. Current distortion power (var) $D_1 = V_1 I_H = V_{1.}\sqrt{\sum_{h\neq1} I_h^2} = S_1\left(THD_I\right)$

b. Voltage distortion power (var) $D_V = V_H I_1 = I_1\sqrt{\sum_{h\neq1} V_h^2} = S_1\left(THD_V\right)$

c. Harmonic apparent power (VA) $S_H = V_H I_H = \sqrt{\sum_{h\neq1} V_h^2 \sum_{h\neq1} I_h^2} = S_1\left(THD_I\right)\left(THD_V\right)$

The fundamental power factor is: $PF_1 = \cos\theta_1 = \dfrac{P_1}{S_1}$

The power factor is defined as: $PF = \dfrac{P_1 + P_H}{S} = \dfrac{\left[1 + \left(P_H / P_1\right)\right] PF_1}{\sqrt{1 + THD_I^2 + THD_V^2 + \left(THD_I THD_V\right)^2}}$

Concluding this section, it can be said that even if Budeanu's resolution of power has been much contested in the last hundred years, many international power quality standards relied on his theory.

Moreover, it has the great merit of opening the way to the study of harmonic analysis in a lot of power quality issues.

Until 2010, Budeanu’s resolution of powers represented until 2010 the fundamentals of the IEEE standard on this matter.

The results of measurements provided by most practical power quality analyzers and test systems rely even nowadays on Budeanu's development.

III. Harmonic Analysis Equipment

To ensure maximum flexibility of harmonic analysis equipment, a modular structure consisting in the following components is generally used:

- A programmable alternating current source that supplies energy, in single or three-phase system, of specified frequency and voltage, having a very low degree of distortion.
- A power analysis and conditioning unit, which creates the mechanical and electrical interface between the AC power source, the equipment under test and the data acquisition system represented generally by a personal computer. The unit provides the necessary signal for the data acquisition system, which uses a fast analog-to-digital conversion board.
- The firmware controlling these devices benefits of an intuitive graphical user interface in the implementation of harmonic and flicker tests. In addition to this firmware, another software package is implemented in the system, which is controlling the alternating and the direct current source.
- Immunity tests, included in IEC/EN 61000-4, are sometimes embedded also in this type of measuring equipment.

Generally, the standards covered by the test equipment belong to the series of EC/EN 61000-3 and IEC/EN 61000-4.

By way of example, Fig. 1 presents a user interface of a commercial three-phase system power quality analyzer.

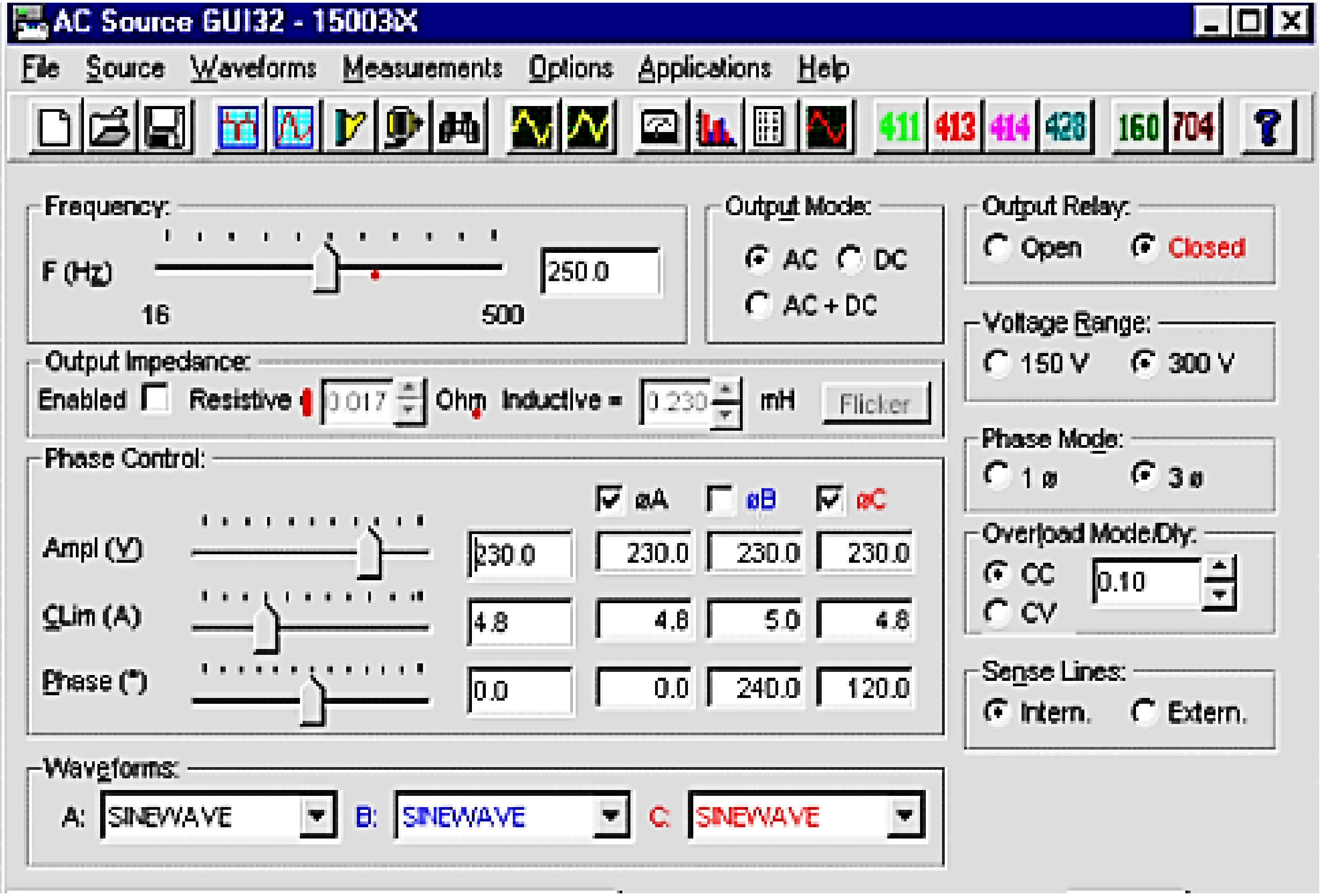


Fig. 1. User interface of a measuring equipment.

The use of a proper type of test, in relation to the equipment under test, is essential for the accuracy of the results.

Consequently, the standard **IEC/EN 61000-3-2: 2014-05** classifies equipment under test with an input current ≤16 A/phase into four classes, setting the limits of the harmonic currents possible to be injected into the public low voltage network by each of the classes.

Class A includes balanced three-phase equipment, household appliances, excluding equipment identified as Class D, tools, excluding portable tools, dimmers for incandescent lamps, audio equipment. Equipment not specified in one of the three other classes shall be considered as Class A equipment.

Class B includes portable tools, arc welding equipment which is not professional equipment.

Class C is reserved to lighting equipment. In conformity with the same standard, lighting equipment is an equipment with a primary function of generating and/or regulating and/or distributing optical radiation by means of incandescent lamps, discharge lamps or LED's.

Included are lamps and luminaires, the lighting part of multi-function equipment where one of the primary functions of this is illumination, independent ballasts for discharge lamps and independent incandescent lamp transformers, ultraviolet (UV) and infrared (IR) radiation equipment, illuminated advertising signs, dimmers for lamps other than incandescent.

Excluded are lighting devices built in equipment with another primary purpose such as photocopiers, overhead projectors and slide projectors or employed for scale illuminating or indication purposes, household appliances whose primary function is not for generating and/or regulating and/or distributing optical radiation but which contain one or more lamps with or without separate switch (e.g. a range hood with a built-in lamp), dimmers for incandescent lamps.

Class D also includes equipment of the following types having a specified power less than or equal to 600 W: personal computers and personal computer monitors, television receivers, refrigerators and freezers having one or more variable-speed drives to control compressor motor(s).

One may observe that class D limits are reserved for equipment that can be shown to have a pronounced effect on the public electricity supply system. Note that equipment that can be shown to have a significant effect on the supply system and belonging to the other classes may be reclassified in future editions of the standard in class D.

The harmonic limits set by the IEC/EN 61000-3-2: 2014-05 are usually embedded in the firmware of test equipment.

Unfortunately, detailed measurements of the distorted powers, in accordance with the IEEE Std. 1459-2010 standard, are not yet available, though it would be very a very strong tool, for producing a refined and accurate harmonic analysis.

IV. Measurements and Discussions

This section is meant to be a comparative harmonic analysis between three case studies using as equipment under test the same load, namely a fluorescent luminaire.

The harmonic analysis was performed for three different supply voltages, using a programmable source.

In the first case the studied load, namely a T8 LED tube light luminaire, was supplied by a purely sinusoidal voltage, while in the next two cases by distorted periodic voltages, synthetized by the authors, and uploaded in the memory of the analyzer.

The two synthesized distorted supply voltages are:

- 10% clipped voltage
- 20% clipped voltage

Measurements in the case of purely sinusoidal supply voltage

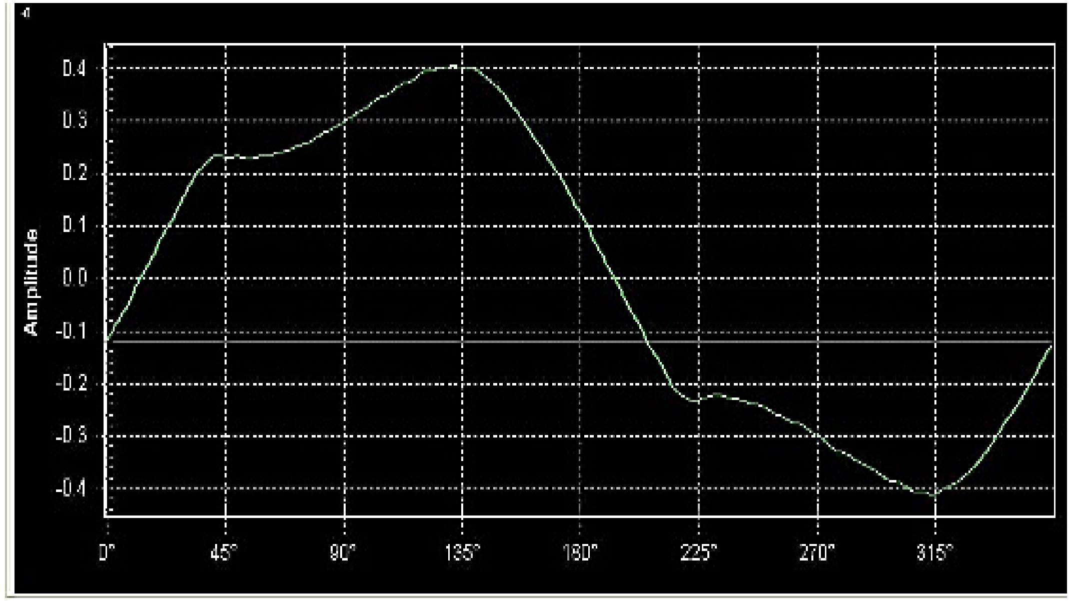


Fig. 2 The waveform of the current drawn for a sinusoidal supply voltage.

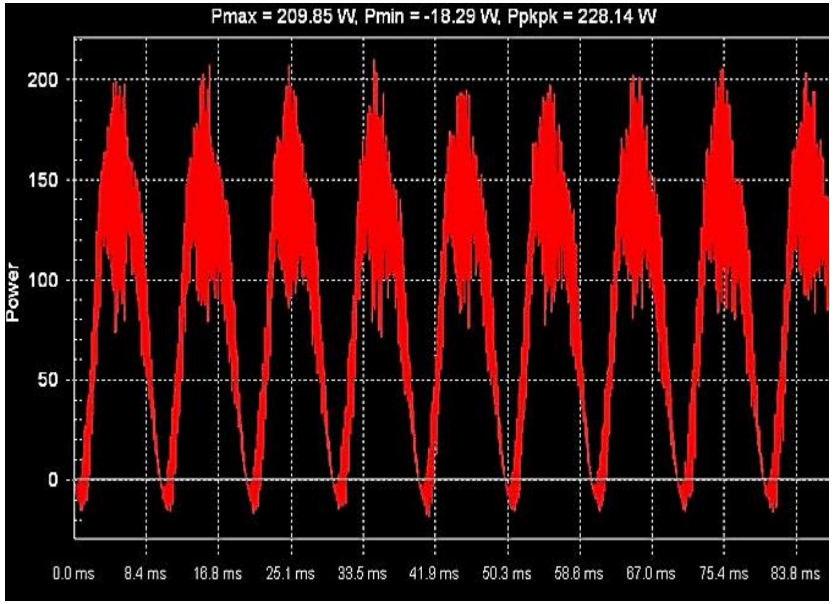


Fig. 3 The instantaneous power drawn for a sinusoidal supply voltage.

Measurements in the case of 10% clipped supply voltage

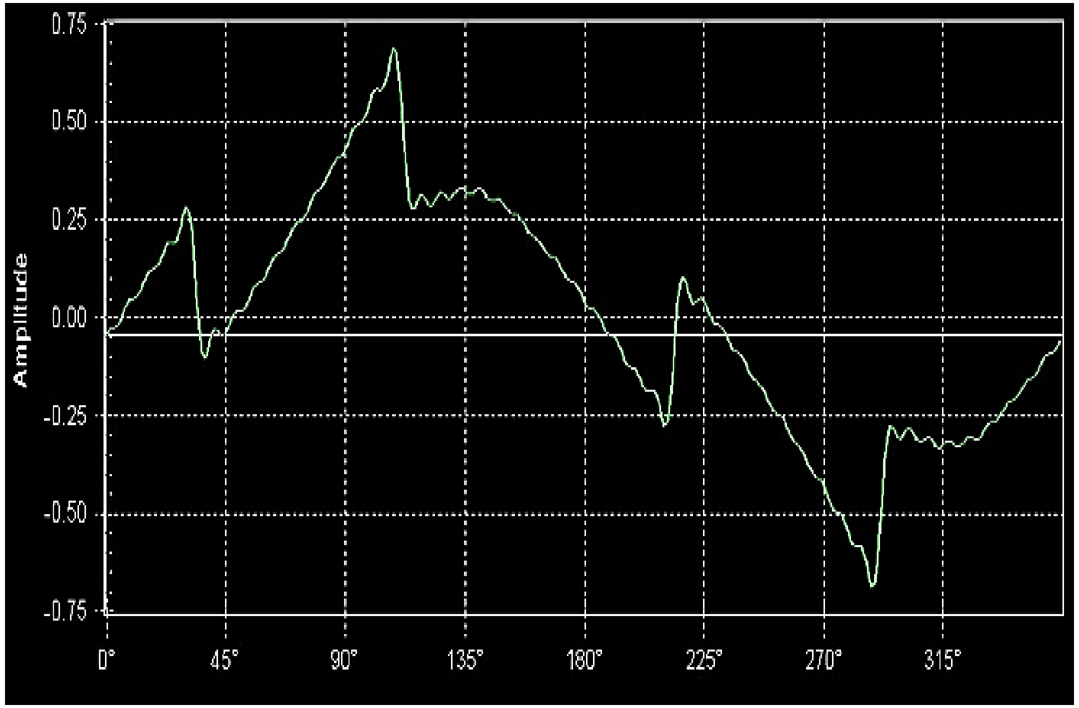


Fig. 4 The waveform of the current drawn for a 10% clipped supply voltage.

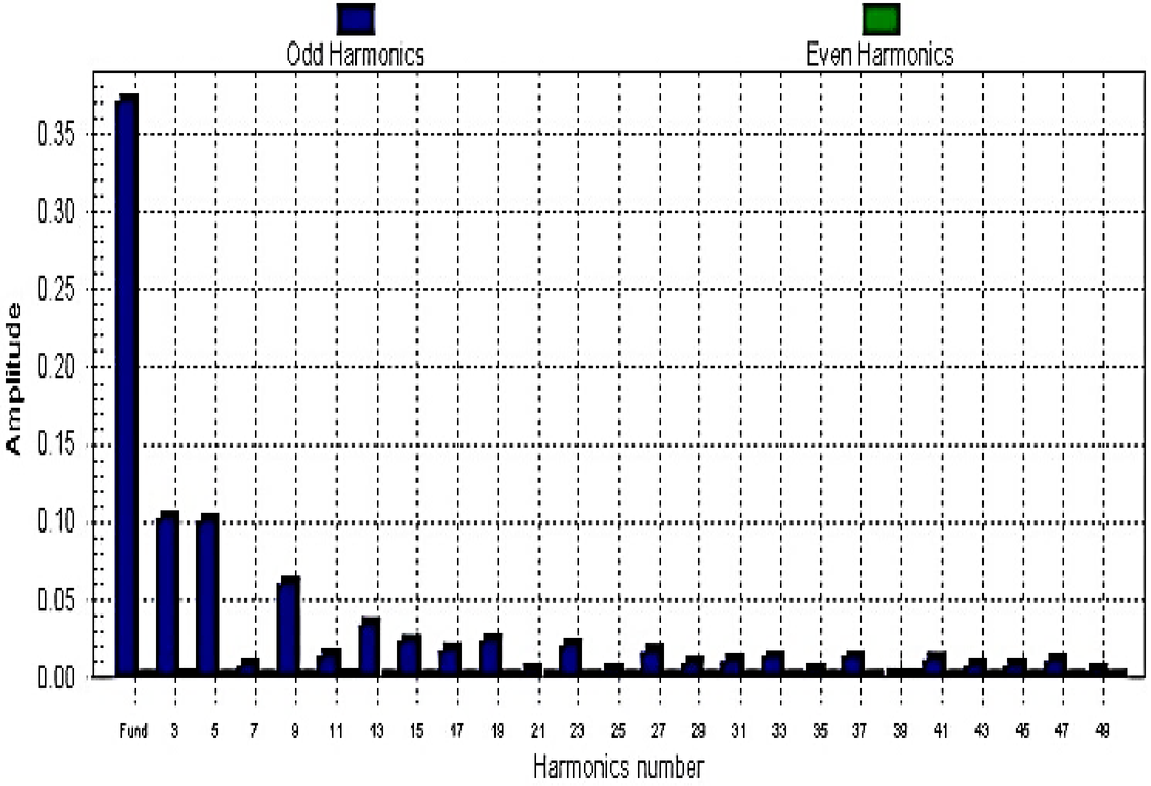
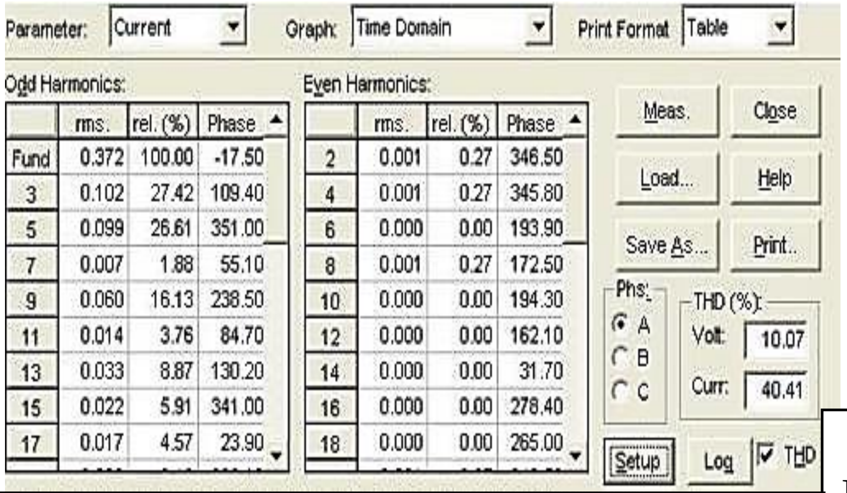


Fig. 7 Harmonic spectrum of the current drawn for a 10% clipped supply voltage.

IEEE CANDO EPE 2020

3rd International IEEE Conference AND workshop in Óbuda on Electrical and Power Engineering



Odd Harmonics:

	rms.	rel. (%)	Phase
Fund	0.372	100.00	-17.50
3	0.102	27.42	109.40
5	0.099	26.61	351.00
7	0.007	1.88	55.10
9	0.060	16.13	238.50
11	0.014	3.76	84.70
13	0.033	8.87	130.20
15	0.022	5.91	341.00
17	0.017	4.57	23.90

Even Harmonics:

	rms.	rel. (%)	Phase
2	0.001	0.27	346.50
4	0.001	0.27	345.80
6	0.000	0.00	193.90
8	0.001	0.27	172.50
10	0.000	0.00	194.30
12	0.000	0.00	162.10
14	0.000	0.00	31.70
16	0.000	0.00	278.40
18	0.000	0.00	265.00

Fig. 5 Upper part of the harmonic analysis window of the current drawn for a 10% clipped supply voltage.

Fig. 6 Harmonic limits of the current drawn for a 10% clipped supply voltage in accordance with class C.

	Frequency	Actual	Limit	% of Limit	Compare
1	50.000	0.358			
2	100.000	0.002	0.007	27.933	Pass
3	150.000	0.104	0.093	111.560	Fail
4	200.000	0.002			
5	250.000	0.105	0.036	293.296	Fail
6	300.000	0.001			
7	350.000	0.007	0.025	27.933	Pass
8	400.000	0.000			
9	450.000	0.062	0.018	346.369	Fail
10	500.000	0.000			
11	550.000	0.015	0.011	139.665	Fail
12	600.000	0.000			
13	650.000	0.034	0.011	316.574	Fail
14	700.000	0.000			
15	750.000	0.024	0.011	223.464	Fail
16	800.000	0.000			
17	850.000	0.016	0.011	148.976	Fail
18	900.000	0.000			
19	950.000	0.024	0.011	223.464	Fail
20	1000.000	0.001			
21	1050.000	0.004	0.011	37.244	Pass
22	1100.000	0.000			
23	1150.000	0.020	0.011	186.220	Fail
24	1200.000	0.000			
25	1250.000	0.005	0.011	46.555	Pass
26	1300.000	0.000			
27	1350.000	0.016	0.011	148.976	Fail
28	1400.000	0.000			
29	1450.000	0.010	0.011	93.110	Pass
30	1500.000	0.000			
31	1550.000	0.009	0.011	83.799	Pass
32	1600.000	0.000			
33	1650.000	0.012	0.011	111.732	Fail
34	1700.000	0.000			
35	1750.000	0.003	0.011	27.933	Pass
36	1800.000	0.000			
37	1850.000	0.012	0.011	111.732	Fail
38	1900.000	0.000			
39	1950.000	0.001	0.011	9.311	Pass
40	2000.000	0.001			

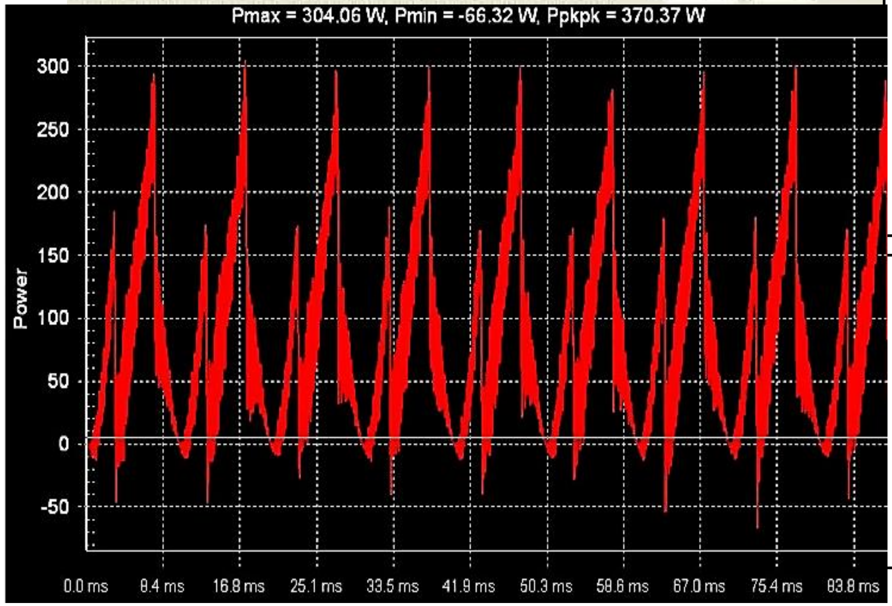


Fig. 8 The instantaneous power drawn for a 10% clipped supply voltage.

November 18-19, 2020

Measurements in the case of 20% clipped supply voltage

Fig. 9 The waveform of the current drawn for a 20% clipped supply voltage.

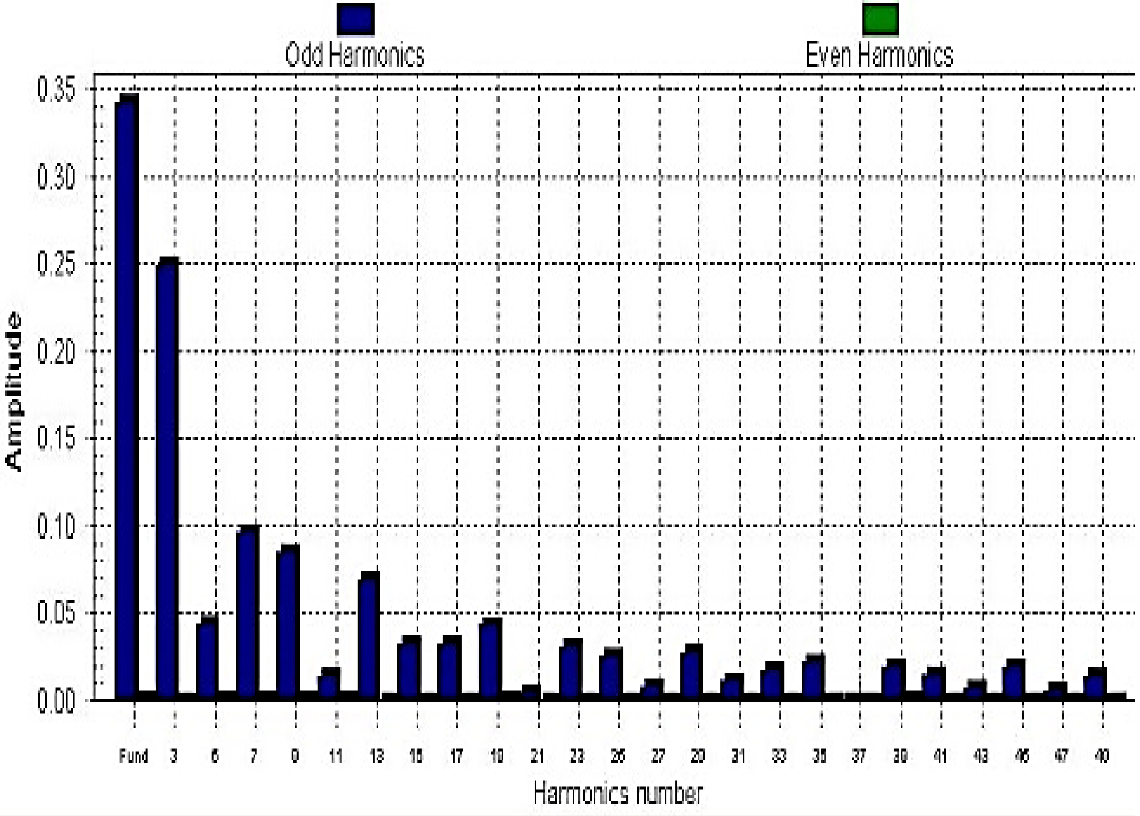
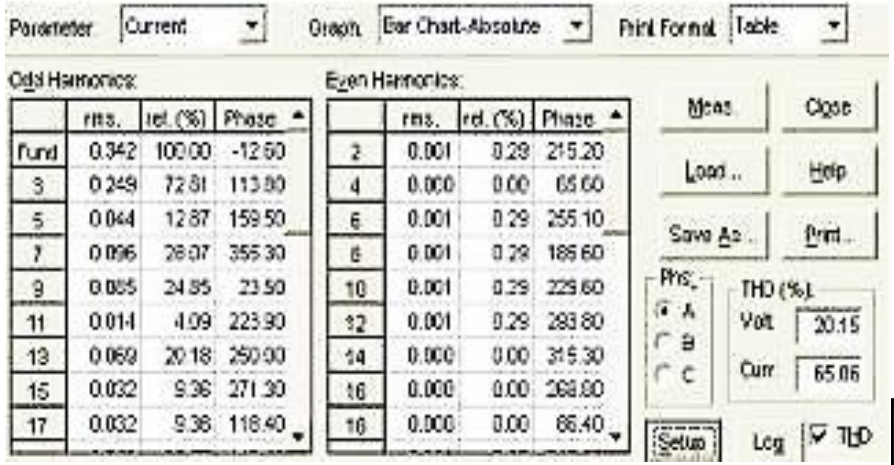


Fig. 12 Harmonic spectrum of the current drawn for a 20% clipped supply voltage.

IEEE CANDO EPE 2020

3rd International IEEE Conference AND workshop in Óbuda on Electrical and Power Engineering



Parameter: Current; Graph: Bar Chart-Absolute; Print Format: Table

Odd Harmonics:

	rms.	rel. (%)	Phase
Fund	0.342	100.00	-12.60
3	0.249	72.81	113.80
5	0.044	12.87	159.50
7	0.096	28.07	355.30
9	0.085	24.85	23.50
11	0.014	4.09	223.90
13	0.069	20.18	250.00
15	0.032	9.36	271.30
17	0.032	9.36	118.40

Even Harmonics:

	rms.	rel. (%)	Phase
2	0.001	0.29	215.20
4	0.000	0.00	65.60
6	0.001	0.29	255.10
8	0.001	0.29	186.60
10	0.001	0.29	229.60
12	0.001	0.29	283.80
14	0.000	0.00	315.30
16	0.000	0.00	268.80
18	0.000	0.00	86.40

Fig. 10 Upper part of the harmonic analysis window of the current drawn for a 20% clipped supply voltage.

Fig. 11 Harmonic limits of the current drawn for a 20% clipped supply voltage in accordance with class C.

	Frequency	Actual	Limit	% of Limit	Compare
1	50.000	0.332			
2	100.000	0.002	0.007	30.120	Pass
3	150.000	0.256	0.072	356.488	Fail
4	200.000	0.000			
5	250.000	0.042	0.033	126.506	Fail
6	300.000	0.001			
7	350.000	0.098	0.023	421.687	Fail
8	400.000	0.001			
9	450.000	0.083	0.017	500.000	Fail
10	500.000	0.000			
11	550.000	0.014	0.010	140.562	Fail
12	600.000	0.000			
13	650.000	0.069	0.010	692.771	Fail
14	700.000	0.000			
15	750.000	0.033	0.010	331.325	Fail
16	800.000	0.000			
17	850.000	0.031	0.010	311.245	Fail
18	900.000	0.000			
19	950.000	0.045	0.010	451.807	Fail
20	1000.000	0.000			
21	1050.000	0.004	0.010	40.161	Pass
22	1100.000	0.000			
23	1150.000	0.033	0.010	331.325	Fail
24	1200.000	0.000			
25	1250.000	0.025	0.010	251.004	Fail
26	1300.000	0.000			
27	1350.000	0.009	0.010	90.361	Pass
28	1400.000	0.000			
29	1450.000	0.027	0.010	271.084	Fail
30	1500.000	0.000			
31	1550.000	0.011	0.010	110.442	Fail
32	1600.000	0.000			
33	1650.000	0.016	0.010	160.643	Fail
34	1700.000	0.000			
35	1750.000	0.022	0.010	220.884	Fail
36	1800.000	0.000			
37	1850.000	0.000	0.010	0.000	Pass
38	1900.000	0.000			
39	1950.000	0.020	0.010	200.803	Fail
40	2000.000	0.001			
41	2050.000	0.015			

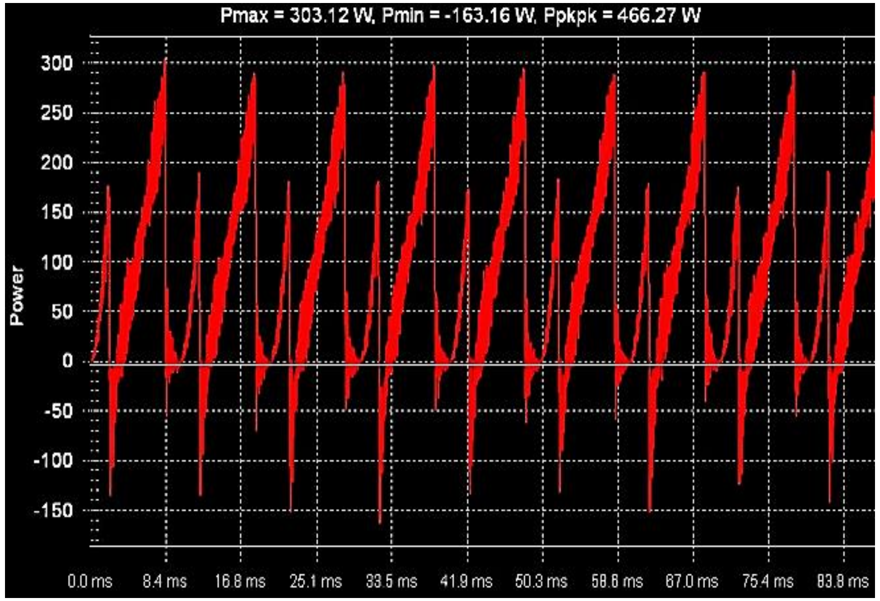


Fig. 13 The instantaneous power drawn for a 20% clipped supply voltage.

November 18-19, 2020

V. CONCLUSIONS

Concluding, at first glance, the 6 W decrease does not seem very significant, but a decrease of over seven percent in energy efficiency could be important in lighting systems of large facilities on medium and long terms.

Obviously, with the decrease of the real power, the illumination level decreases accordingly.

Therefore, additional costs are required to reach the level of illumination imposed by the regulations in this matter.

It is obvious that harmonic components greatly affect energy efficiency.

In the examples displayed in the paper, the distortion of the supply voltages and the nonlinearities of the load were moderate. However, in practice one may encounter many situations in which the harmonic content could be much higher, significantly affecting the energy efficiency of the electric systems of the end users and of the adjacent electric systems as well.

On the other hand, the new refined resolution of power, given by the standard IEEE Std. 1459-2010, represents at this moment a climax of the long-term debate about power resolution that lasted for a century and may be will continue.

In the general opinion and in the opinion of the authors as well, the rigor of this resolution allows the ones who analyze powers, to know exactly which practical effects are due to every category of power component.

V. Conclusions

Currently manufactured analyzers, along with the complex equipment for testing power quality, allow a high-performance analysis of the phenomena involved, both in time and frequency range, as the case studied presented in this paper revealed.

However, affordable equipment is not yet capable of resolving apparent power into the components depicted in the above-mentioned IEEE Std. 1459-2010 standard and consequently to produce a more detailed analysis of power in nonsinusoidal systems.

Hopefully, the near future will bring to the scientific community and to the practitioners the fulfillment of this important goal.

Thank you for your attention!