Analysis of power quality field measurements and considerations on the power quality standard

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Abstract—The aim of this paper is to present and analyze a series of Power Quality (PQ) field measurements that took place in different sites of the Greek electric grid, such as a nutrition industry, a photovoltaic park with nominal power of 100kW, a Waste Water Treatment Plant (WWTP), a food industry, a Town hall and in several buildings of two educational institutes. PQ monitoring seems to be very important in Greece due to the fact that there are still no legislative rules covering this issue neither from the users' nor from the grid administrator's side. The results of these measurements are used in a research project which aims to create a PQ evaluation model using fuzzy sets methodology in order to calculate a total PQ index of a specific point. In this paper an analysis of these measurements is presented. PQ disturbances are recorded according to EN 50160, while a comparison with PQ limits of EU countries is introduced.

1. Introduction

The widespread use of electricity and the complexity of new load types have led to increasing needs of control and monitoring of supply voltage. The majority of end-users do not monitor any Power Quality (PQ) disturbances of supplied power to their installation. On the other hand a lot of voltage fluctuations are responsible for many damages and malfunctions of end-users' electrical and electronic equipment. Voltage fluctuations can be recorded and analyzed using appropriate measuring equipment.

Large Scale Power Generation units as also Transmission System Operators (TSOs) do monitor and record such events in order to tackle fault situations in generation and transmission system. But there is lack of PQ events' monitoring that occurs mainly in low and medium voltage.

The monitoring is very important in order to capture PQ events and correlate them with fault situations in electrical installations. Moreover the recording of such events is very useful for energy management and energy saving techniques [1]-[6]. Statistical data that can be extracted from PQ monitoring will answer many questions about the electrical equipment aging and how PQ events act throughout the time. PQ should be monitored not only for identifying PQ issues, but also for ranking the measuring point from PQ point of view. This procedure will help for future protection of the users and the network [7].

The aim of this paper is to present, analyze and classify the results of several PQ field measurements at different points of the Greek electric grid. The analysis will be used in return to a Fuzzy Total Power Quality Index (FTPQI) model for verification of the membership functions for each disturbance [8].

During previous years several PQ measurements have been performed. In this paper seven different locations are presented. The locations were chosen after users' claim for PQ issues in the past. The measurement campaign was initiated during year 2013 and is still ongoing. The measurements mainly took place in the central distribution board of each installation. The main idea was to capture PQ events and their severity in electrical equipment in different points of the network. During that period the duration of each PQ disturbance and the frequency of these events has been recorded and analyzed. Users' opinion has been of great importance in order to correlate PQ events with fault situations in their installation.

Finally the measurement results, analysis and the estimated reason for PQ event observation are presented. An attempt of evaluating EN50160 PQ limits is introduced.

2. Monitoring PQ characteristics

For the needs of measurement campaign two measuring equipment were used[1]:

1. Power Quality Analyzer Hioki 3196 with Clamp On Sensors 9661
2. Power Quality Analyzer Fluke 345 with Clamp On Sensors iflex6000s

Both measuring equipment can capture and monitor all PQ characteristics as described in international standards [9].The minimum time period required in order to extract safe results is one week for continuous disturbances and a year record for discrete disturbances, according to EN 50160 [9].

In this paper the minimum time period measured was one week when in most of the situations the measurements were performed for two weeks. For discrete events, such as interruptions and Voltage dips, users' records were used.

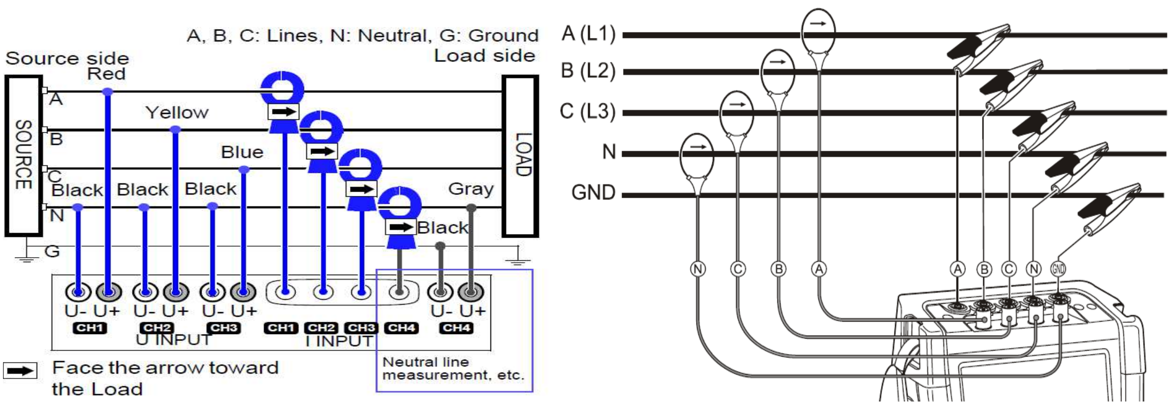

Figure 1: (a) Connection of Hioki 3196 Analyzer and (b) Connection of Fluke 435 Analyzer

[1]The measuring equipment was not obtained using ARCHIMIDES III research program funds, due to administrative issues during the bidding process. The equipment used is private and is provided from the members of research team.

During this measurement campaign all PQ characteristics, as described in EN50160, were recorded. The most important of them for the needs of this research proposal are the following:

a/a	PQ Characteristic	Time period	Measurement Hioki 3196	Measurement Fluke 435
1	Long interruptions	1 year	events	events
2	Short interruptions	1 year	events	events
3	Voltage Dips/swells	1 year	events	events
4	Voltage variation	1 week	% inside limits	events
5	Frequency variation	1 week	% inside limits	events
6	Voltage unbalance	1 week	% inside limits	events
7	Voltage Harmonics	1 week	% inside limits	events
8	Rapid Voltage changes	1 day	events	events
9	Flicker severity	1 week	% inside limits	events
10	Transient Overvoltage	-	waveform	-

Table 1: PQ events that were measured and recorded according to EN50160

PQ characteristics as presented in Table 1 can be separated in two main categories, a) Discrete PQ Disturbances (DPQD) and b) Continuous PQ Disturbances (CPQD).Measurement time and the limits of each disturbance are the main purpose for this separation. DPQD happen rarely, but last more than a period. The amount of these events as also the duration in a particular time frame (as shown in Table 1) indicate the severity of their existence in a network. CPQD on the other hand are more often and may occur a lot of times in a day. According to [4] these PQ characteristic should be inside specific limits (column (2) of Table 2) for the most of the time period (column (3) of Table 2).

CPQD (1)	Limit (2)	In a week (3)
Freq A	±1%	99.5%
Freq B	-6%/4%	100%
V vari A	±10%	95%
V vari B	-15%/10%	100%
Flicker	Plt<1	95%
Unbalance	2%	95%
THD	8%	95%
Harmonic	Special limits[4]	

Table 2: Limits for continuous PQ disturbances

For Voltage and Frequency there are two limits to be checked. For voltage RMS value most of the measurements should not vary more than 10% from nominal values, while all the measurements should be inside the limits of ‘V vari B’ of Table 2. The same happens also for frequency. Most of the measurements should not vary more than 1% of nominal frequency, while it is not acceptable that a measurement appears outside limits of ‘Freq B’ of Table 2.

3. Description of Measurement Sites

Specialized questionnaires were used in order to collect information of significant users and chose the most appropriate once for measurements. Seven different locations were chosen to measure PQ characteristics. The sites were all across Greece trying to analyze different grid topologies and weaknesses.

All consumers are Medium Voltage users, while the PV Park is Low Voltage user. The measurement equipment was connected in Low Voltage Main Board, trying to capture most of the events that affect the installation.

Due to the fact that there are several similarities in the loads of the sites, they can be supposed as representative users. The sites and the main load type for each one are shown in Table 3.

a/a	Substation	Main Load Type	Location
1	Photovoltaic park	Sensitive Electronic Equipment (inverter)	Inland Greece - End of MV line
2	Nutrition industry	Motor – compressor	Inland Greece close to Substation (SS)
	Educational institute 1		Close to High Voltage (HV)Substation (SS)
3.1	-Library	Chiller – PCs	
3.2	-PC Lab	PCs – Lights	
3.3	-Building Z	Chiller – Lights - Motors	
4	WWTP	Motors	Island Greece end of MV line
5	Food industry	Motors – Sensitive drive equipment	Greece Inland – close to HV SS
6	Educational institute 2	Motors – PCs - Lights	Greece Inland
7	Town Hall	Offices - Chiller	Greece Inland – City Centre

Table 3: Measurement Sites and load type for each

All above mentioned sites contain significant number of sensitive electronic equipment. For a PV Park, a WWTP, a food industry and a nutrition industry the continuity of power supply is of great importance. In addition PV Park is very vulnerable on other PQ characteristics, because deviations from nominal values may lead to loss of production. In educational institutes the deviations of power supply may lead to several damages in experimental and equipment. In addition lack of power supply may lead in total failure the educational or research procedure.

CPQD on the other hand may lead to significant damages in sensitive equipment and aging of three phase loads (motors, etc).

All users have complained for various troubles in operation of electronic equipment in the past, but due to absence of measurement equipment in the installation no connection with the aim of the problem could be officially justified

4. Measurement Results Review & Analysis

4.1 General

The research team initiated measuring PQ characteristics, presented in this paper, in year 2013. During last two years several measurements have been performed to various sites. In this paper seven of them are presented that have been monitored for enough time, giving results reliable for further evaluation. The time frame for each location is presented in Table 4.

a/a	Substation	Time Period	Duration
1	Photovoltaic park	28/10/13-5/11/2013	7 days
2	Nutrition industry	18/4/2014-26/4/2014	8 days
	Educational institute 1		
3.1	-Library	29/9/2014-20/10/2014	21 days
3.2	-PC Lab	20/10/2014-4/11/2014	15 days
3.3	-Building Z	5/9/2014-23/9/2014	18 days
4	WWTP	1/4/2015-15/4/2015	14 days
5	Food industry	25/5/2015-8/6/2015	14 days
6	Educational institute 2	8/6/2015-23/6/2015	16 days
7	Town Hall	10/7/2015 – 24/7/2015	15 days

Table 4: Time periods and duration of field measurements

The measurements performed in these sites have been analyzed and organized for all during different time periods. In order to be able to compare and evaluate the measurements a categorization is necessary. In paragraph 4.2 and 4.3 the review of the measurements organized in two groups a) DPQD and b) CPQD is presented.

4.2 DPQD

At each set of measurements many events appeared that were in full compliance with EN 50160 standard. Overall throughout the period of the measurements, which lasted 113 days, appeared 96 voltage dips, zero swells, one interruption and zero transients. Table 5 shows the duration of the measurements at each substation and the total events that appeared at each one of them.

a/a	Installation		Measurement Duration	Discrete Events	
				Dips	Inter.
1	Photovoltaic Park		7	0	0
2	Nutrition Industry		8	1	0
3.1	Educational Institute 1	Library	21	28	0
3.2		PC Lab	15	0	0
3.3		Building Z	18	38	0
4	WWTP		14	16	0
5	Food industry		14	5	1
6	Educational Institute 2		16	8	0
7	Town Hall		15	3	0

Table 5: Number of discrete events at each substation

In Table 5 Dips and Interruptions are recorded when no swells and transients were monitored during measuring period.

In addition to the voltage and frequency absolute values, the duration of the phenomenon plays an important role in power quality. In the CBEMA and ITIC characteristics the immunity zones of equipment to disturbances coming from the network are illustrated [11]. Table 6 presents the three worst voltage dips and the duration of them. These values are within the limits of the referred characteristics in all the measurements points.

In Table 6, the numbers in Dip 1, Dip 2 and Dip 3 classification are given in “voltage value (in V)/duration (in ms)”.

a/a	Installation		Dips	tDip classification (voltage/duration)		
				Dip 1	Dip 2	Dip 3
1	Photovoltaic Park		0	-	-	-
2	Nutrition Industry		1	209.22/ 640	-	-
3.1	Educational Institute 1	Library	28	151.32/ 90	190.65/ 60	193.31/ 70
3.2		PC Lab	0	-	-	-
3.3		Building Z	38	189.65/ 60	193.82/ 60	194.79/ 160
4	WWTP		16	192.30/ 90	196.35/ 128	201.27/87
5	Food industry		5	148.90/ 93	195.00/ 80	198.20/ 90
6	Educational Institute 2		8	204.40/ 40	204.50/ 50	205.10/ 60
7	Town Hall		3	188.00/120	203,40/10	205.10/50

Table 6: Worst dips at each substation of measurement

In Figure 2, the CBEMA and ITC characteristics for the food industry are presented.

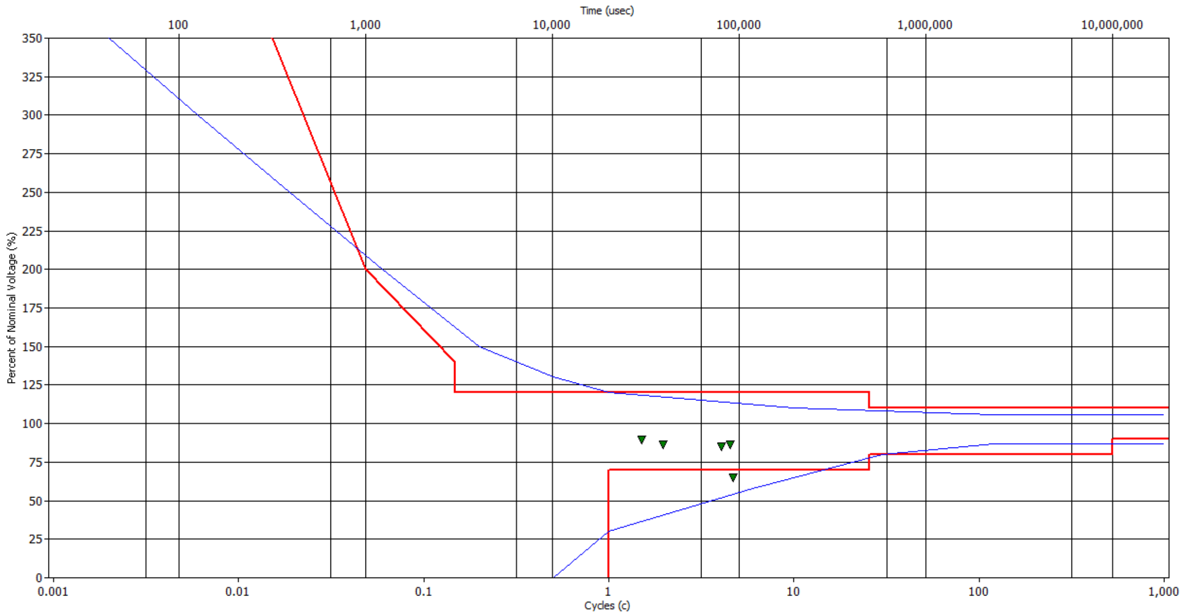

Figure2: CBEMA and ITIC characteristics of food industry

In Table 7 the maximum and minimum values of the voltage and the frequency in all the measurement points are presented. The duration of the minimum values of the voltage at the library and the food industry is very short (see Table 6). Therefore all the dips are in accordance to the EN 50160.

a/a	Installation		Voltage (in V)		Frequency	
			Min	Max	Min	Max
1	PhotovoltaicPark		220.6	246.18	49.89	50.117
2	Nutrition Industry		209.22	244.89	49.891	50.099
3.1	Educational Institute 1	Library	151.32	242.58	49.873	50.105
3.2		PC Lab	213.05	240.62	49.881	50.132
3.3		Building Z	189.7	240.34	49.001	50.094
4	WWTP		192.3	238.08	49.25	50.5
5	Food industry		148.9	241.47	49.919	50.105
6	Educational Institute 2		204.4	238.57	49.954	50.103
7	Town Hall		188.00	223.0	49.98	50.02

Table 7: Minimum and maximum values of voltage and frequency

4.3 CPQD

In Table 2 the limits for CPQD are presented. At the end of measuring time period the 10min average values are checked for complying with the limits of column (2) of Table 2. If they comply with the limits there is no event recorded. Any excess of the limits is counted as PQ event. The percentage of 10 min intervals that comply with the limits should be at least equal to the value of column (3) in Table 2 for each CPQD for the measured time period.

Most of the PQ characteristics were 100% inside the limits. Few situations have been recorded were the samples of Flicker and Harmonic Distortion are not 100% complying with the limits of column (2) of Table 2. More specifically, in only one measuring point (PC Lab of Educational institute 1) the 10 min average samples with THD less than 8% in a week time (the first of two weeks measured) were 93.8% (<95%). For the same location, during the second week of measurements, the samples with THD<8% were above 95%.

Taking into consideration several PQ problems recorded in measurement locations during the last years, it seems that the EN50160 limits in some occasions cannot provide fully reasonable analysis and explanation of the problem. Even more, it is important to notice that in sites with more than one week measurements, there are significant differences between different time periods.

The main issues recorded in each site are presented in Table 8.

a/a	Installation		Main Issues recorded
1	Photovoltaic Park		A lot of interruptions per year (>30)
2	Nutrition Industry		A lot of instantaneous waveform distortions due to compressor start
3.1	Educational Institute 1	Library	Flicker issue (week 01/10/2014-08/10/2014 96.4% inside limits)
3.2		PC Lab	Harmonic issue (week 28/10/2014 – 03/11/2014 93.8% inside limits)
3.3		Building Z	Flicker issue (96.7% inside limits in days 05/09/2014 – 09/09/2014)
4	WWTP		Flicker issue (97.4% inside limits in days 21/03/2015 – 28/03/2015)
5	food industry		5 dips in 2 weeks (in each one the production had to restart)
6	Educational Institute 2		8 dips in 2 weeks (inside limits of SEMI chart)
7	Town Hall		3 dips in 2 weeks (inside limits of SEMI chart)

Table 8: Main issue monitored for each location

The issues recorded in Table 8 seem to be inside acceptable limits (except Harmonic in PC lab of Educational Institute 1 and the interruptions in PV Park). Though during measurement period a lot of wave distortions have been recorded that cannot be classified to any of PQ disturbances, but they are able to create troubles in sensitivity loads. For example in Figure 3, the transient overvoltage created due to load of large capacitors in Building Z of educational institute 1 is depicted. This event is repeated every 12 hours. These events are not rapid voltage changes, cannot be easily captured, but able to create problems to sensitive electronic equipment like PCs' digital clocks.

In Figure 4, a waveform distortion in PV Park is presented. Though during that time there is no power production present, a small rapid deviation in current waveform is enough to create waveform distortion also in voltage. This fact indicates the existence of a weak network. This explains the reason why over thirty interruptions in that grid location are appeared. In Figure 5, in Library of educational institute 1 there is specific distortion in Voltage waveform (in the upper and lower part of the wave) due to the presence of Harmonics in current of electronic equipment like PCs and chiller.

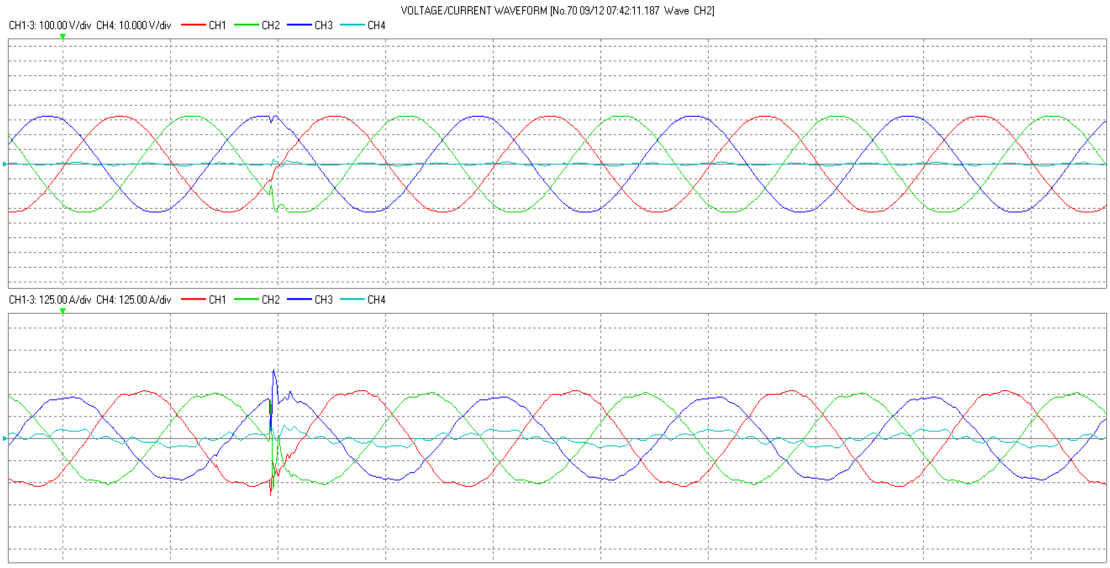

Figure 3: Wave distortion in Voltage and current of Z building

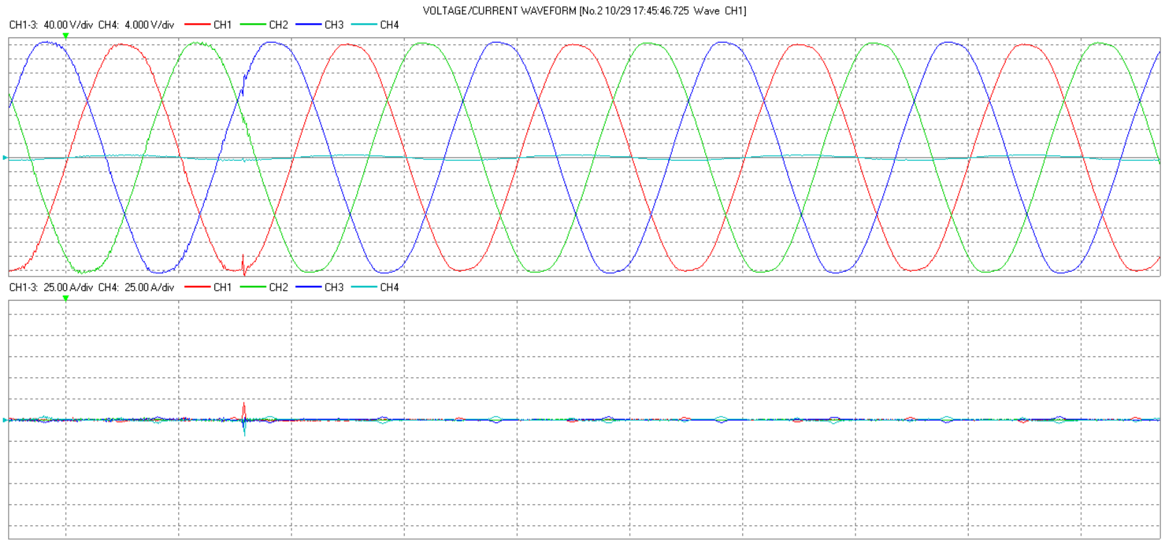

Figure 4: Wave distortion in Voltage and current of PV Park

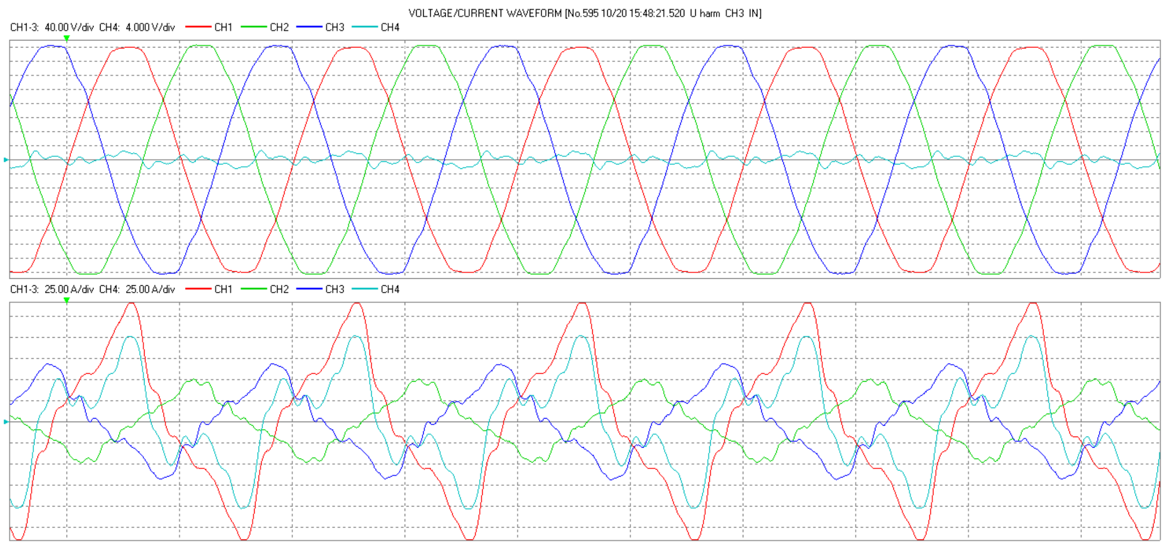

Figure5: Waveform Distortion in Voltage and Current in Library of Educational institute 1

In Figure 6, the results of a spike current in voltage waveform in Waste Water Treatment Plant (WWTP) can be identified. However, it should be noticed, that the WWTP is at the end of the MV line and the network is not very stable.

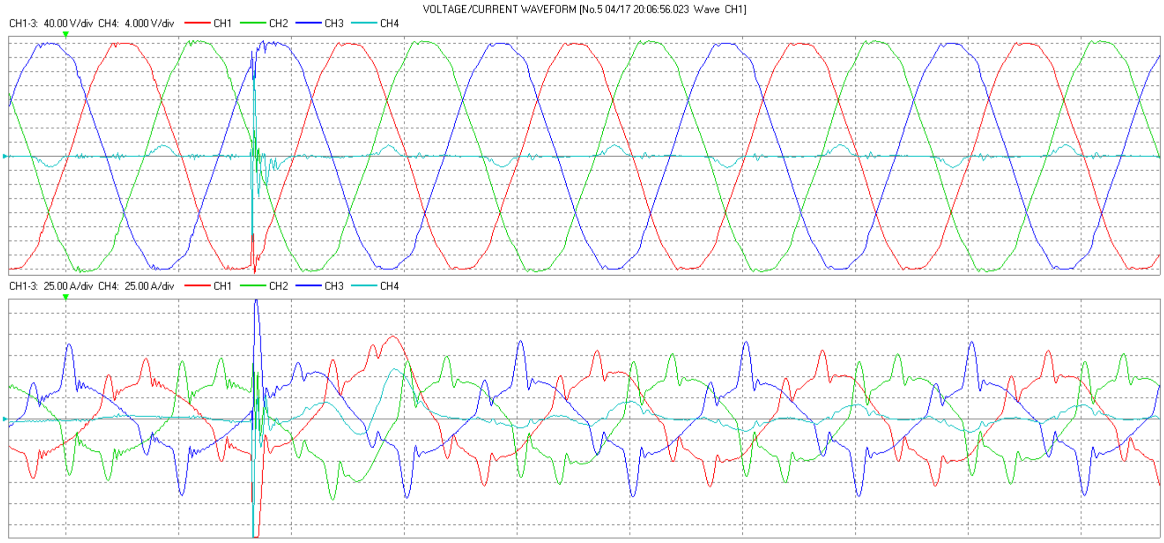

Figure 6: Waveform distortion in Voltage and current in a WWTP

In Figure 7, the results of a motor start are obvious in Voltage waveform.

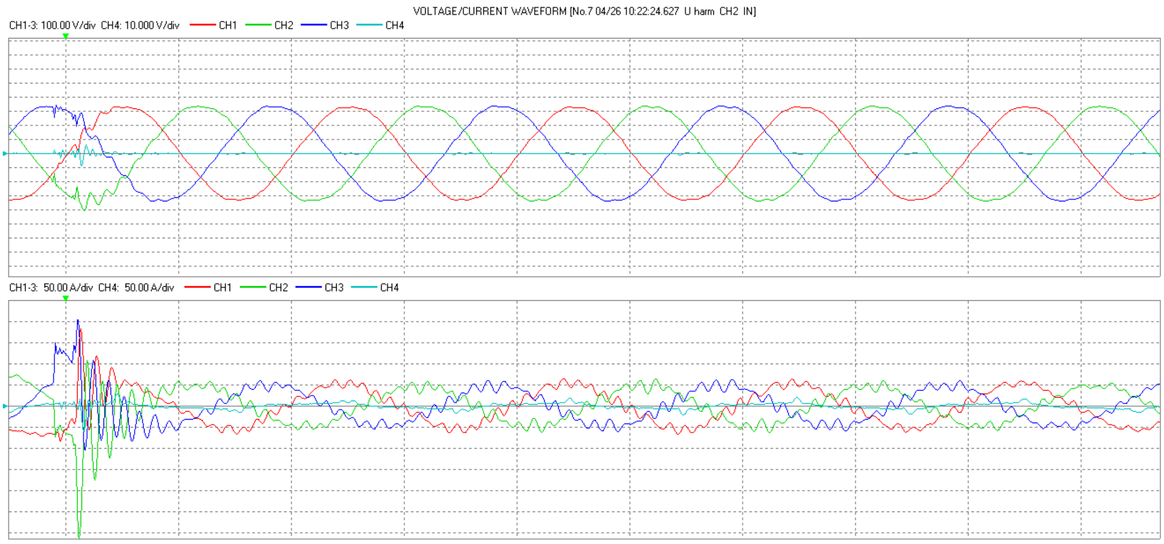

Figure7: Waveform Distortion of Voltage and current in Nutrition industry

All the above recorded data show that even if the disturbances are inside the limits described by the standards, many deviations that cannot be classified and play significant role to standards values may occur. On the other hand, these events may be responsible for a lot of damages inside an industry or in an office facility. That indicates that a further and more detailed research beyond the known standards must be attempted, adopting stricter limits in order to have a less vulnerable electric network.

5. EU Countries Regulations for PQ

A lot of countries do not follow the standards as presented in [1], but have adopted other, stricter, limits. For example Italy (IT) has adopted different regulations for different operational situations in high voltage. In Table 9 acceptable limits for Hungary (HU), Portugal (PT), Estonia (ES), Norway (NO), Netherlands (NL) and Italy (IT) for voltage variations are presented.

Voltage disturbances	Indicator	Integration period	Time	Limit	Country (voltage level)
Supply voltage variations	r.m.s. voltage	10 min	95%	±7.50% of UN	HU (LV)
	r.m.s. voltage	10 min	100%	±10% of UN	HU (LV), SE (HV,MV,LV)
	r.m.s. voltage	1 min	100%	+15%/-20% of UN	HU (LV)
	r.m.s. voltage	10 min	95%	±5% of UN	PT (HV)
	r.m.s. voltage	10 min	95%	±7% of UN	ES (MV, LV)
	r.m.s. voltage	1 min	100%	±10% of UN	NO (LV)
	r.m.s. voltage	10 min	95%	±10% of UN	NL (MV)
	r.m.s. voltage	10 min	100%	+10%/-15% of UN	NL (MV)
	r.m.s. voltage	10 min	99.9%	±10% of UN	NL (HV)
	r.m.s. voltage	10 min	95%	+5.33%/-4.66% of UN	IT (HV) [150 kV, normal]
	r.m.s. voltage	10 min	100%	+10%/-6.66% of UN	IT (HV) [150 kV, normal or alarm]
	r.m.s. voltage	10 min	100%	+13.33%/-14.66% of UN	IT (HV) [150 kV, emergency or restoration]
	r.m.s. voltage	10 min	95%	±5.30% of UN	IT (HV) [132 kV, normal]
	r.m.s. voltage	10 min	100%	+9.84%/-9.09% of UN	IT (HV) [132 kV, normal or alarm]
	r.m.s. voltage	10 min	100%	+13.6%/-15.15% of UN	IT (HV) [132 kV, emergency or restoration]
	r.m.s. voltage	10 min	100%	+10%/-15% of UN	IT (MV) [temporary islanding operation of normally interconnected MV networks]
Flicker	Pst	-	95%	≤0.35	CY (HV, MV, LV)
	Plt	-	95%	≤0.35	CY (HV, MV, LV)
	Pst	-	95%	≤0.8	CZ (HV, MV, LV)
	Plt	-	95%	≤0.6	CZ (HV, MV, LV)
	Pst	-	100%	≤0.85 (planning level)	IT (HV)
	Plt	-	100%	≤0.62 (planning level)	IT (HV)
	Pst	-	95%	≤1.2	NO (MV, LV)
	Pst	-	95%	≤1	NO (HV)
	Plt	-	100%	≤1	NO (MV, LV), PT (HV)
	Plt	-	100%	≤0.8	NO (HV)
	Pst	-	100%	≤1	PT (HV)
	Plt	-	100%	≤5	NL (HV, MV, LV)
Voltage unbalance	Vun	10 min	95%	≤1%	IT (HV)
	Vun	10 min	100%	≤2%	NO (HV, MV, LV), SE (HV, MV, LV)
	Vun	10 min	100%	≤3%	NL (MV, LV)
	Vun	10 min	99.9%	≤1	NL (HV)
Harmonic voltage	THD	10 min	100%	≤1%	IT (HV)
	THD	10 min	100%	≤ 8% 0,23≤U≤35kV ≤ 3% 35≤U≤245kV	NO (HV, MV, LV
	THD	1 week	100%	≤5%	NO (MV, LV)
	Individual	10 min	95%	Table	PT (HV)
	Individual	10 min	100%	Table	NO (HV, MV, LV)
	Individual	10 min	100%	Table (as in EN 50160)	SE (HV, MV, LV)
	THD	10 min	95%	≤8%U<35kV ≤6%35≤U<150kV	NL (HV, MV, LV)

Table 9: Limits in EU countries for Voltage variations and CPQD from nominal value [5]

From Table 9, it is remarkable to notice, that Countries like Hungary located in Central Europe with many electrical interconnections with other countries have adopted limits stricter than EN50160.

It is also important to point that the measurements presented in this paper have been performed using EN50160 standard. Consequently, that means that Voltage variations inside the acceptable limits of Table 2 are not supposed to be events. According to Table 9 if the measurements have been performed with Voltage variation limits of Portugal (that is a network similar to the Greek one) the amount of such CPQE would be much different than measured. In Estonia for example the Voltage limits are set at 7% (while in EN50160 are set at 10%). Same results are also concluded if we apply different limits in other disturbances. In Czech Republic the acceptable limit for flicker severity in LV is under 0.35, while in EN50160 this limit is set at 1. It is obvious that the number of flicker issues which have been already identified using EN50160 limits, would have been more if a different, stricter standard had been applied.

In order to understand the importance of these limits and to efficiently identify them several additional measurements should be performed. The trend of last decade is to change old analogue energy meters with smart meters that can meter and analyze also PQ issues. In Table 10 EU countries that use Smart meters are presented. It is obvious and of great importance to increase the parameters that can be monitored through smart meters. If all PQ disturbances as presented in Table 1 could be monitored, then a huge database could be created suitable enough to identify the acceptable limits of PQ in a network location and improve Power Quality.

It is obvious from Table 10 that most of the Administrators are monitoring only Voltage Variations, while in Portugal and Greece (two of the weakest networks in EU) only a small number of parameters is measured.

Countries	Smart meters?	Voltage quality monitoring possible?	Which parameters are (or can be) monitored?
Austria	Yes	Under analysis	At the moment, no nation-wide smart metering is in place, but a number of on-going projects with a discussion of functionality definition (e.g. supply voltage variations, unbalance).
Finland	Yes	Partly	Some smart meters can monitor supply voltage variations and voltage dips.
France	Yes	Partly	Supply voltage variations (from 10 minute intervals to 1 minute intervals).
Greece	Yes	Partly	Smart meters of MV customers can monitor voltage dips and swells.
Italy	Yes	Partly	Supply voltage variations.
Latvia	Yes	Partly	Supply voltage variations, voltage dips and swells, harmonic voltage.
Lithuania	Yes	Partly	Frequency, supply voltage variations.
The Netherlands	Yes	Partly	Supply voltage variations.
Portugal	Yes	No	No measurement of voltage quality parameters possible.
Sweden	Yes	Partly	Some smart meters can monitor supply voltage variations.

Table 10: Monitoring PQ in EU countries [10]

6. Conclusions

Even if no significant declinations are recorded according to the known standards during the on-field measurements at 10 different sites, the PQ disturbances should be monitored and recorded during a long period (e.g. 1 year) in order to sufficiently analyze PQ of a site. Measurements carried out at points of the network, such as islands and industrial areas, didn't show significant problems in the time periods indicated by the standard. However, no reliable conclusion can be obtained from this fact, because in the aforementioned points of the network, significant harms to consumers' equipment have been occurred during the last year, according to customer observations.

Measurements will be used for calculating a unique Fuzzy Total Power Quality Index (FTPQI) [7] for every measured point of the electric network according to Archimedes research proposal. FTPQI could be used by the system administrator giving a reliable way to check the total PQ of electric networks.

This measuring campaign contributed significantly to understand that the limits of EN50160 are quite lenient and consequently not appropriate for this research proposal. In order to answer the question *"How good Power Quality of a point is"* stricter PQ limits for designing membership functions of [7] must be adopted.

Useful conclusions can be obtained, if two similar Power Quality Analyzers are placed at the same site, set –however- to different limits for PQ events. In this case the researchers will be able to compare the results on Power Quality when applying standard EN50160 limits or stricter limits of power quality, indicated by the operational needs of the consumers' equipment. Such measurements will assist the target of structuring a common, stricter PQ standard all over EU countries.

Finally, it is important to introduce a new type of smart meter, which can measure most of PQ characteristics, in order to extract significant conclusions about PQ events and their consequences to end-users. The extended installation of smart meters will help each network administrator to identify the reasons of equipment failures and to introduce successful policies for efficient network and customer protection.

Acknowledgements

This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: ARCHIMEDES III. Investing in knowledge society through the European Social Fund.

European Union European Social Fund
OPERATIONAL PROGRAMME EDUCATION AND LIFELONG LEARNING investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS MANAGING AUTHORITY
Co-financed by Greece and the European Union
NSRF 2007-2013 EUROPEAN SOCIAL FUND

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