Distortion of line voltage in weak low-voltage networks due to large scale installation of energy saving lamps

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ABSTRACT: The aim of this research is to identify the levels of the harmonic distortion caused in weak low-voltage networks due to large-scale installation of compact fluorescent lamps (CFLs). The research uses data from field measurements of the harmonic content and other characteristic measurements of the PV station supplied electric network of the island of Arki. It is examined whether this weak low voltage electric network is able to keep the total harmonic distortion factor at all buses under 5%, as more and more CFLs are installed. The autonomous photovoltaic (PV) station, which supplies power to the island load, is itself a harmonic generator. This fact combined with other highly non-linear loads -such as CFLs- causes serious problems at the network power quality as undesirable harmonic components are induced. The whole network is simulated and 3 scenarios of CFL installation extent are considered, so that the harmonic flow analysis reveals the influence in the power quality. The conclusions drawn from this analysis are important and must be taken into account in every electric network design.

Keywords: Compact fluorescent lamps, Harmonics, Harmonic distortion, Power quality, Photovoltaics.

I. INTRODUCTION

Grid circulating harmonics is an issue of great importance. International standards (e.g. IEC 61000) define harmonic distortion limits under which the energy producing companies are obliged to operate. Better energy quality (stable frequency and voltage, high power quality, "clean" waveforms) is the target, since high harmonic existence represents a possible source of faults and troubles for loads and for the electric system equipment. All harmonic sources and effects have been well identified and presented [1-4].
Arki is a small Greek island of the East-Aegean Sea, the population of which reaches 100 inhabitants. It is supplied by a 25kWp Autonomous Photovoltaic (PV) Power Station. The PV station uses a self-commutated dc/ac inverter, which is considered to be an important harmonic source [5, 6, 7]. It was proved [6] that the harmonic content of the voltage waveform at buses of the electric network was richer in harmonics when the PV station was on, rather than when the back up Diesel generator did supply the system.
Elimination techniques used for these harmonics are many and they are applied successfully in most cases in the Photovoltaic Systems. Such techniques are the SPWM, MPWM and some conventional ones like filtering and specific transformer connections [7, 8]. However, the harmonics reduction techniques at the output of the PV station of the island of Arki are conventional.
This is the reason why a relatively high (2.5–4.5%) Total Harmonic Distortion of the line voltage (THDv) is present. After the PV station other non-linear loads produce more harmonic currents that circulate in the power network and when added with other harmonic currents of similar phase serious problems on electrical appliances are caused [4]
Especially, CFLs are defined as highly non-linear loads producing a high current THD factor, while CFLs with electronic gear have extremely distorted current with a THD usually exceeding 100%. On the other hand, all electric power corporations world-wide suggest the use of energy saving lamps such as the CFLs. Such a suggestion must be thoroughly studied and analysed especially on case studies like small size low voltage networks supplied by autonomous PV stations, where the THD content is already high. Otherwise, the result of the widely expanded use of CFLs will be the increase of voltage THD factor beyond the internationally set limits of 5% [9, 10], a fact that causes serious consequences to the customer side.
On the field of the harmonic content of CFLs or the behaviour of CFLs under various exploitation conditions a large number of papers are published [11-14]. On the contrary, not many studies are published dealing with the influence of CFLs to the power network or with the definition of their maximal presence without leading to excessive voltage distortion [15, 16, 17].
The principal goal of this research is to identify the levels of the harmonic distortion caused in weak low-voltage networks due to large-scale installation of compact fluorescent lamps (CFLs). For that reason, a specific simulation methodology is developed which uses as input field measurements of the voltage harmonic content at the output of Arki PV station, laboratory measurements of CFL produced harmonic currents, various electric network data etc. The whole electric network is simulated and 3 scenarios of CFL installation extent are considered. After preparing all necessary information, a three-phase harmonic flow analysis takes place for every CFLs installation scenario and reveals the influence in the power quality of the system. The results are of great significance.

II. DESCRIPTION OF THE NETWORK

The 25kWp PV power plant that supplies the weak low-voltage electric network of the island of Arki has 688 panels in total (43 series of 16 panels each), while each panel consists of 40 solar cells (Photon Technology) in series and has a nominal power of 26Wp [18].

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The PV station of the island is equipped with a 3–phase static inverter, which serves the purpose so feed a.c. consumers that require 230V/400V supply voltage. More specifically, it is a self–commutated inverter model of AEG "G 220 D 400/43/2 rgf–V30". The DC input supply voltage is 220V (+/-15%), the rated a.c. voltage is 3x400V (full load neutral) and the Rated Power at $\cos\varphi = 1$ is 24kW. Its efficiency is between 73% and 91% when the load varies between 10–100% [18, 19]. The power electronic section consists of six thyristor stacks combined into two six–pulse 3-phase full–wave bridge circuits. That means that each three out of the six identically assembled low-loss Mc Murray circuits form a 3-phase full-wave bridge circuit configuration. With periodic sequence of triggering the main thyristors, each 3–phase full-wave bridge circuit supplies a separate 3–phase a.c. system, while the second system is lagging in time by 30°el with respect to the first system. The electric power is transmitted by means of two transformers; one assigned to the first system and the other one to the second but both ending at a common secondary winding [19, 20].
The low-voltage network topology of Arki along with the data of the distribution lines (cable type and length) is presented in Fig.1.

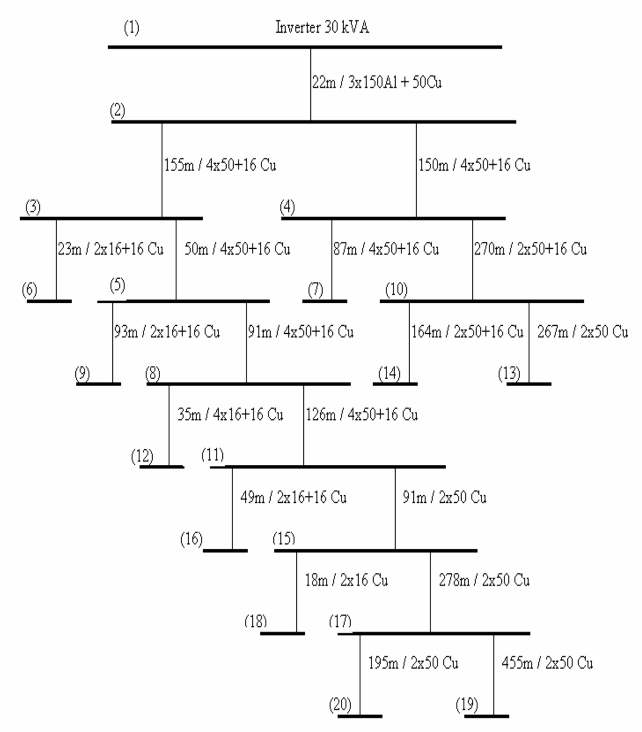

Fig. 1. Arki - The low-voltage electric network topology

III. FIELD MEASUREMENTS OF HARMONIC DISTORTION ON ARKI ELECTRIC NETWORK

The THD of a voltage waveform according to IEEE definition is:

$$THDv = \frac{\sqrt{V_2^2 + V_3^2 + ... + V_N^2}}{V_1} \cdot 100 \qquad (1)$$

where V_1 is the root-mean square of the fundamental and V_N the root–mean square of the N–order harmonic component.
Apart from the PV power station, the demand of the island can be covered by a Diesel station, which operates only in emergency cases (too many cloudy days, PV station service etc). It was proved [6] that at the island of Arki the PV station inverter injects larger harmonic content than the Diesel station does. This conclusion was proved by measuring the voltage THD after connecting the PV station and disconnecting the Diesel and vice-versa. So the distorted supply voltage from the PV station is a fact.
Measurements were also performed at numerous preselected lines along the electric grid and at houses and other customers as presented in [6]. The measuring instrument was the Multiver 3S of Dossena. The measurements were being obtained every 500 microsecond (2kHz) in each sample procedure. Each sample contains 3 voltage and 4 current "sub-samples". The analysis of the samples was performed using the Fast Fourier Transform method. The appropriate software enabled an analysis of harmonic components up to the 19th order (0-1000 Hz).
The harmonic content at the output of the PV station is a very important input data for the simulation. Among many field measurements the one considered as the most common and reliable has the harmonic spectrum shown in Table 1.

Table 1. Harmonic spectrum (%) of the PV station

Fund	3rd	5th	7th	9th	11th	13th	15th	17th	19th
100	0.9	2.2	0.3	0.1	1.3	1.8	0.3	0.3	0.0

At the island of Arki, the voltage THD at different places in the electric grid was measured to be 1.85%-5.30% [6]. This means that there are certain positions of the electric grid that exceed the limits for the THD factor, such as the one placed at Heliou's House [6]. These measurements were performed while the whole load was 8.5kW. This fact proves how weak and sensitive the local network is under possible non-linear loads. However, International Electrotechnical Commission in IEC 61000–3–2 suggests limits for the current distortion caused by household appliances and similar electrical equipment [9].

IV. CFL HARMONIC DISTORTION MEASUREMENTS

In order to obtain real and reliable data concerning the exact current harmonic content of CFLs so that to use them in the simulation program, many samples of CFLs were tested in the laboratory in order to determine their odd order harmonic spectrum. Such lamps do not produce even order harmonic currents. The nominal power of the CFLs that are widely used in the households of the island is 20W and 23W. It must be also noticed that the phase difference between the supply voltage waveform and the fundamental current waveform of the tested lamps is negligible. However, the power factor is very low (0.4–0.5) due to the considerable harmonic content of current. The measurement of the current harmonics of these CFLs is presented in Table 2.
All data from the measurements are properly used as input in the simulation model in order to estimate the influence of CFLs to the network voltage distortion.

Table 2. Normalised amplitude (%) of CFL harmonics

Harmonic order	20 W	23 W
3	88.9	88.2
5	71.1	69.1
7	48.9	47.4
9	28.9	27.3
11	18.9	18.1
13	16.7	16.1
15	12.6	12.0
17	6.8	6.1
19	2.5	1.7
THD (%)	**130.5**	**127.7**

V. SIMULATION

All the electrical characteristics of the network (i.e. distribution lines, load) have to be accurately simulated in order to obtain reliable results. The simulation of the electric network is performed using the PSCAD v3.0.6 software.

All cables of the electric network shown in Fig.1 are simulated with their actual lengths, which have been measured in site. According to type and the cross-section of the cables the resistance and the inductance are calculated and set as input data as well.

The island's network supplies 60 houses. Public Power Corporation (PPC) does not allow high energy demanding electrical appliances. PPC also suggests gas for cooking, solar panels for hot water and oil heaters for heating. The most used electrical appliances are incandescent lamps, TV sets, irons and low power refrigerators. Field measurements at typical residences showed that the average daily loading (200W–400W) was lower than the installed load. Three typical loads (A: 200W, B: 300W, C: 400W) are considered as shown in Table 3. Some buses of the real network supply three residences. In that case, the loads of the three residences are added and presented as one (D–type).

Table 3. Low loading of typical residences obtained by field measurements

Load Type	Load characteristics
A	P=200W; $\cos\varphi$ =0.78; Q=160.5Var
B	P=300W; $\cos\varphi$ =0.85; Q=186.0Var
C	P=400W; $\cos\varphi$ =0.87; Q=227.0Var
D	P=900W; $\cos\varphi$ =0.84; Q=573.0Var

For the whole island, three load profile scenarios are simulated and examined in this study:

1st scenario: This load profile corresponds to the measured low loading of Table 3 and sums up to 9kW total load (30% of the inverter power).

2nd scenario: This load profile corresponds to a possible higher loading of 18kW total load (60% of the inverter power).

3rd scenario: This load profile corresponds to the maximum loading of the inverter 27kW (90%).

It is observed that there is a load-asymmetry between the three phases. Actually, almost 40% of the load is supplied by the S and T phases. This is taken into account while simulating the load in the 3–phase network.

Load statistical data of the island of Arki show that the load profile of each house consists of lighting (50%) and other consuming appliances (50%).

Initially, the electric network was analysed considering only linear loads, while the THD of the inverter output was considered to be equal to one of the less distorted measured values (3.14%). This is the most favourable network initial condition (almost ideal). In that case the calculation of the THD at all buses was found to be 3.14% as expected.

Then, all scenarios examine the variation of voltage harmonic distortion at all network buses assuming that all incandescent lamps are replaced with CFLs. More specifically, all 100W incandescent lamps are replaced with 23W CFLs and all the 75W incandescent lamps are replaced with 20W CFLs. In both cases, laboratory measurements showed that the CFLs of 23W and 20W have the same maintained luminous flux with the replaced incadescent ones of 100W and 75W respectively.

The rest loads are considered to be linear. This consideration is not true but it represents the less distorted load profile of the network. This means that the calculation results will provide the minimum values of harmonic distortion. In fact, the harmonic content will be higher due to the non-linear behaviour of the rest of the loads.

The current harmonics induced by the CFLs of every house are simulated with odd order harmonic current sources (150Hz, 250Hz etc.) as shown in Table 2.

The electric network of Arki, after the addition of the harmonic current of CFLs is fully described in Fig. 2.

VI. RESULTS AND DISCUSSION

The calculation results for all scenarios are given in Table 4. The most significant conclusions derived from Table 4 for all the examined scenarios are presented and discussed as follows:

1st scenario: Total Load 9kW (30%)

- Maximum THDv of line voltage: 6.7%.
- THDv exceeds the limit of 5% at 5 out of 42 buses of the network.
- Largest THDv difference before/after CFLs installation: 4% i.e. the power quality is not affected. This means that in case of a network with ideal source the voltage THD will never exceed the limit of 5% at any bus.
- Highest THDv appears at one terminal bus (No.19), where a large load is connected.
- There are network buses where the THDv decreases up to 1% (harmonic cancelling).
- At some buses the 9th voltage harmonic component exceeds the limit of IEC 61000–3–6.

2nd scenario: Total Load 18kW (60%)

- Maximum THDv of line voltage: 15.3%.
- THDv exceeds the limit of 5% at 17 out of 42 buses of the network. In fact, THDv exceeds 8% at 7 buses.
- Largest THDv difference before/after CFLs installation: 12.34%. This means that even in case of an ideal source there are buses of the network with voltage THD>5%.
- Highest THDv appears at 9 terminal buses.
- There are network buses where the THDv decreases up to 1% (harmonic cancelling).
- More than one harmonic component exceeds the limits of IEC 61000-3-6. This takes place at buses with THDv higher than 5% i.e. at buses that require special care in order to improve the power quality.

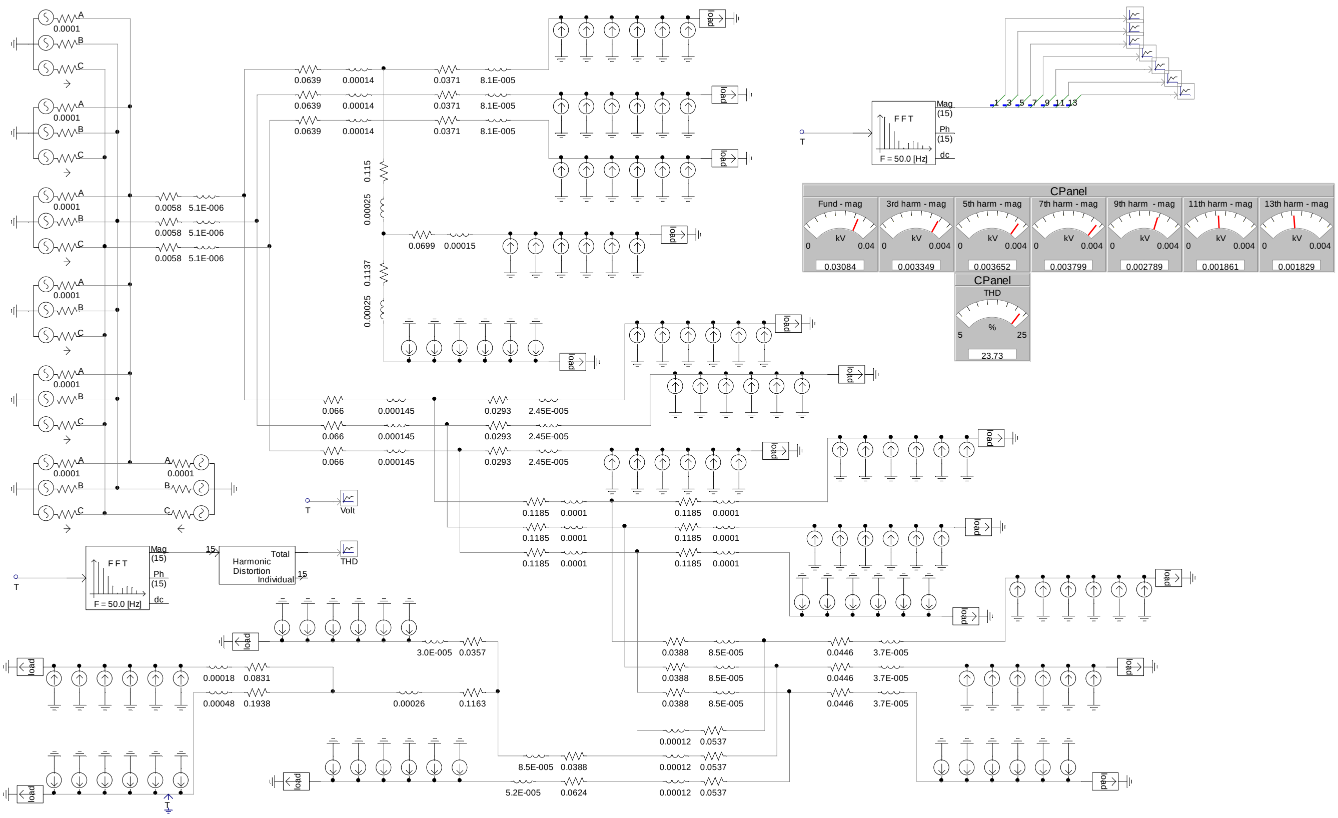

Fig. 2. The electric network of Arki (the current sources represent the harmonic content of CFLs)

3rd scenario: Total Load 27kW (90%)

- Maximum THDv of line voltage: 23.7%.
- THDv exceeds the limit of 5% at 27 out of 42 buses of the network. In fact, THDv exceeds 8% at 15 buses.
- Largest THDv difference before/after CFLs installation: 20.9%. This means that even in case of an ideal source there is a remarkable number of network buses with THDv>5%.
- THDv exceeds the limit of 5% at 14 terminal buses of the network that require special care and at other 13 middle buses where no specific limits are set.
- There are network buses where the THDv decreases up to 0.6% (harmonic cancelling).
- Many harmonic components exceed the limits of IEC 61000-3-6. As in the 2nd scenario, this takes place at buses with THDv above the limits i.e. at buses that require special care in order to improve the power quality.

Other general results

The load–asymmetry forces the inverter to work to the extent that the S and T connected loads are sufficiently covered, while R absorbs only a small percent of energy. Most probably this asymmetry enhances the 3rd and 5th harmonics existence. However, it is certain that the harmonic cancelling procedure, which happens at all buses, is less effective. The conclusion is that, while designing an autonomous electric network (especially a weak one) special care must be given in the equal load distribution on each phase at every bus and in total throughout the network.

Given that the rest network loads were considered linear (which is not true) one comes to the conclusion that the each time calculated voltage THD factor is the least possibly expected, when replacing incandescent lamps with CFLs. This also means that even in that ideal case (linearity of the rest loads) CFLs increase the voltage THD factor near to the acceptable limits of 5% only in the 1st scenario, because the circulating currents are very low.

Scenarios 2 and 3 prove that, if the total load of the island is near to the half (60%) or even 90%, then the voltage THD factor is unacceptable at most or all buses of the network respectively. Accordingly, this means that CFLs installation in that extent (30% and 45% of the islands' load) leads to exceed of international voltage THD limits.

It is observed that phase S of the 19th bus has the largest harmonic distortion in every examined scenario. This bus supplies one of the largest loads. Such loads are connected to buses 18 and 20 on the same phase (load asymmetry). These buses also appear to have large voltage THD factor. Such network buses can be considered as "sensitive buses" and are perfect for field measurements of the THDv factor, since they provide the worse picture that the harmonic distortion could have throughout the network.

Taking into account the above arguments and facts, one can come to the following conclusion: If the voltage THD factor at a "sensitive bus" is under the international acceptable limits, then there will be no THDv exceed problem throughout the electric network.

The harmonic distortion problem is a complex one, especially in weak low–voltage networks, such as those supplied by autonomous PV stations. In such cases, every significant change of load synthesis to achieve energy saving must be thoroughly studied. Otherwise problems like unacceptable harmonic distortion will rise. Moreover, it may be not cost effective such a large-scale load substitution since the cost of giving solution to the created problems is possibly larger than the energy saving profit itself.

Table 4. Voltage THD (%) at all electric network buses for the three scenarios

	1st scenario: Total Load 9kW (30%)			2nd scenario: Total Load 18kW (60%)			3rd scenario: Total Load 27kW (90%)		
	Incadescent lamps	CFLs	Difference	Incadescent lamps	CFLs	Difference	Incadescent lamps	CFLs	Difference
Bus	**THD (%)**	**THD (%)**	**%**	**THD (%)**	**THD (%)**	**%**	**THD (%)**	**THD (%)**	**%**
1T	3.180	3.253	0.073	3.180	3.253	0.073	3.180	3.254	0.074
1S	3.185	3.258	0.073	3.185	3.258	0.073	3.185	3.258	0.073
1R	3.181	3.254	0.073	3.181	3.254	0.073	3.181	3.254	0.073
2T	3.179	3.282	0.103	3.179	3.313	0.134	3.178	3.344	0.166
2S	3.184	3.198	0.014	3.183	3.141	-0.042	3.183	3.089	-0.094
2R	3.180	3.269	0.089	3.180	3.284	0.104	3.180	3.298	0.118
3T	3.169	3.443	0.274	3.158	3.729	0.571	3.147	4.090	0.943
3S	3.156	2.168	-0.988	3.130	2.220	-0.910	3.107	3.228	0.121
3R	3.166	3.858	0.692	3.152	4.562	1.410	3.138	**5.317**	2.179
4T	3.161	3.655	0.494	3.143	4.312	1.169	3.126	**5.114**	1.988
4S	3.182	3.069	-0.113	3.178	2.890	-0.288	3.175	2.725	-0.450
4R	3.179	3.323	0.144	3.177	3.395	0.218	3.175	3.469	0.294
5T	3.165	3.629	0.464	3.151	4.178	1.027	3.146	4.841	1.695
5S	3.143	2.031	-1.112	3.106	3.858	0.752	3.073	**6.383**	3.310
5R	3.159	4.244	1.085	3.138	**5.497**	2.359	3.118	**6.859**	3.741
6T	3.169	3.465	0.296	3.157	3.782	0.625	3.146	4.179	1.033
6S	3.156	2.155	-1.001	3.130	2.246	-0.884	3.106	3.306	0.200
6R	3.166	3.868	0.702	3.151	4.586	1.435	3.137	**5.358**	2.221
7T	3.159	3.706	0.547	3.140	4.453	1.313	3.121	**5.358**	2.237
7S	3.180	2.996	-0.184	3.175	2.754	-0.421	3.171	2.538	-0.633
7R	3.178	3.355	0.177	3.175	3.462	0.287	3.172	3.574	0.402
8T	3.163	3.677	0.514	3.147	4.311	1.164	3.131	**5.076**	1.945
8S	3.129	2.372	-0.757	3.080	**5.368**	2.288	3.036	**8.767**	5.731
8R	3.153	4.549	1.396	3.127	**6.175**	3.048	3.101	**7.917**	4.816
9T	3.163	3.728	0.565	3.147	4.419	1.272	3.131	**5.240**	2.109
9S	3.142	2.048	-1.094	3.104	3.992	0.888	3.071	**6.607**	3.536
9R	3.158	4.337	1.179	3.136	**5.724**	2.588	3.114	**7.228**	4.114
10T	3.135	4.617	1.482	3.093	**6.795**	3.702	3.052	**9.193**	6.141
11T	3.163	3.677	0.514	3.147	4.311	1.164	3.131	**5.076**	1.945
11S	3.111	3.145	0.034	3.045	**7.493**	4.448	2.986	**12.010**	9.024
11R	3.147	4.870	1.723	3.114	**6.882**	3.768	3.083	**9.013**	5.930
12T	3.163	3.715	0.552	3.145	4.402	1.257	3.129	**5.227**	2.098
12S	3.129	2.387	-0.742	3.079	**5.421**	2.342	3.035	**8.852**	5.817
12R	3.153	4.585	1.432	3.126	**6.261**	3.135	3.100	**8.056**	4.956
13T	3.122	**5.210**	2.088	3.068	**8.209**	5.141	3.016	**11.420**	8.404
14T	3.128	4.968	1.840	3.078	**7.640**	4.562	3.030	**10.530**	7.500
15S	3.098	3.809	0.711	3.021	**9.050**	6.029	2.952	**14.370**	11.418
16R	3.145	**5.009**	1.864	3.110	**7.209**	4.099	3.077	**9.537**	6.460
17S	3.072	**5.293**	2.221	2..972	**12.270**	9.298	2.883	**19.220**	16.337
18S	3.097	3.902	0.805	3.018	**9.268**	6.250	2.948	**14.710**	11.762
19S	3.048	**6.730**	3.682	2.927	**15.270**	12.343	2.819	**23.730**	20.911
20S	3.063	**5.833**	2.770	2.955	**13.410**	10.455	2.859	**20.940**	18.081
Min	**3.048**	**2.031**	**-1.112**	**2.927**	**2.220**	**-0.910**	**2.819**	**2.538**	**-0.633**
Max	**3.185**	**6.730**	**3.682**	**3.185**	**15.270**	**12.343**	**3.185**	**23.730**	**20.911**

VII. CONCLUSIONS

The calculations presented in this paper show that the power quality in weak PV systems is very sensitive to non-linear loads. The use of energy saving technologies (e.g. CFLs) in order to decrease the power consumption in these networks may result in unacceptable distortions in the network line voltage. Among the main objectives of the energy management of such networks is to reduce the energy demand and to supply acceptable power quality. It seems that the accomplishment of the first goal is in opposition to the other. An important parameter for energy saving strategies is the use of CFLs with electronic gear. Measures to that direction must be designed carefully after a thorough investigation of the network. As shown from the simulation, a replacement of incandescent lamps with CFLs more than 30% leads to unacceptable values of the voltage factor THD (> 5%). The problem is enhanced, if the existence of other non-linear loads is also to be taken into account.

Therefore, in order to achieve and maintain –especially in weak systems– the desired power quality and performance, appropriate directions should be given to the consumers concerning the suggested types of electrical equipment (load quality) and the upper limit of their load (load quantity) that will not increase the THD of line voltage beyond the accepted limits.

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