The influence of replacement of incandescent lamps with compact fluorescents to the harmonic distortion in non-interconnected island grids

I. CHATZAKIS, G.A. VOKAS, F.V. TOPALIS
School of Electrical and Computer Engineering, Photometry Laboratory
National Technical University of Athens
Iroon Politechniou 9, 157 80 Athens
GREECE

Abstract: - The aim of this research is to examine the consequences caused to the electric power quality and especially to the harmonic distortion of Kythnos network by a possible extended use of compact fluorescent lamps (CFLs). The electric power network of the island of Kythnos is supplied by an autonomous diesel station (ADS), an 100kWp grid-connected photovoltaic (PV) power plant and two wind farms of a total 665kW power. The increased use of CFLs, other non linear loads and renewable energy systems in weak electric systems is a matter of research as far as the power quality is concerned. For that purpose, a simulation of the 3-phase medium voltage network of Kythnos Island and its loads under different CFLs installation scenarios was performed. The use of the appropriate simulation software allowed a detailed harmonic flow analysis of the electric system and its harmonic distortion characteristics. From this analysis important conclusions are drawn in every electric network design project.

Key-words: - compact fluorescent lamps, harmonic distortion, power quality, renewable energy sources.

1. Introduction

It is well known that energy producing companies are obliged to supply excellent energy quality to the customers following the national and international limits and standards [1, 2]. High harmonic existence represents a possible source of faults and troubles for loads (motors, home electrical appliances, computer systems etc.) and for the electric system equipment (capacitors, cables etc.). All harmonic sources and effects have been well identified and presented in the past [3-5].

The increased use of renewable energy sources and energy saving measures follow worldwide accepted strategic guidelines. Most renewable energy sources that produce electric power use power electronics (converters, inverters), which represent also a harmonic source [2, 3, 6, 7]. In Greece, the Public Power Corporation (PPC) has installed Photovoltaic (PV) systems on some islands with rated power 25-100 kW. These PV stations use dc/ac inverters and are either autonomous (Arki 25 kWp, Antikythira 25kWp, Gavdos 25 kWp) or interconnected to the electric grid of the island (Kythnos 100kWp, Sifnos 60kWp). In most cases the harmonic content of the voltage waveform at points of the electric network of a weak system was richer in harmonics when a PV station was on rather than when the ADS did supply the system [8, 9]. The techniques used for the elimination of these harmonics are many and they are applied successfully in most cases in the modern renewable energy systems [10, 11].

Energy saving measures include the replacement of incandescent lamps with Compact Fluorescent Lamps (CFLs) with electronic gear. CFLs consume 80 % less energy than incandescent lamps, but they are a nonlinear load and inject into the network high harmonic currents. In every weak electric power system, all non-linear loads (motors, refrigerators, CFLs, etc.) under normal conditions produce harmonic currents that circulate in the power network and when added with other similar phase harmonic currents serious problems on electrical appliances (e.g. TV sets, refrigerators, computers etc.) are caused [12, 13]. 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%. That is the reason why there is a limitation for their share in the total installed load. This share is determined by the requests from international standards concerning compatibility levels for voltage harmonics. On the other hand, all electric power corporations world-wide suggest the use of energy saving (low energy consumption) lamps such as the CFLs. Such a suggestion must be thoroughly studied and analysed especially on case studies like small size low or medium voltage networks supplied by hybrid systems consisted of ADS, PV and wind farms, where the THD content is -most possibly- 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 8% [1], a fact that causes serious consequences to the customer side.

A lot of studies that examine the harmonic content of CFLs or the behaviour of CFLs under various exploitation conditions have been presented [14-19], while a few studies are performed about the influence of CFLs to the power network wherein they are [15, 19, 20].

In order to estimate the harmonic distortion, caused by the extensive use of CFLs in electric systems that Renewable Energy Systems are already installed, a simulation of the Kythnos island distribution network was performed. Kythnos network is representative for this project, as it is supplied by a 2MW ADS, an 100kWp PV station and a 665kW wind farm. Till 1994 the Kythnos PV plant was using a self-commutated inverter, while the system was using batteries as well. Since then, a line-commutated grid connected inverter is responsible for the dc-ac conversion of the produced electric power by the PV system.

For the simulation of this 3-phase medium voltage network, real data were used. The electronic fluorescent lamps were simulated according to the emitted currents harmonic components. Recently, at the Photometry laboratory of N.T.U.A. the behaviour of the CFLs have been studied and the extent of the emissions of the harmonic currents were recorded.

Regarding the voltage harmonic components at the output of the Photovoltaic and wind farms the measurements were extracted from previous doctoral theses. The harmonic content of the line voltage was measured at the output of the PV station and at several places of the network. Also, field measurements were performed at selected transformers of the network providing data for transformers power factor, voltage and current THD factors and existence of harmonic currents at their neutral node.

It will be shown that the harmonic distortion caused by CFLs is considerably higher than other sources, including the PV and the wind farms, and is increased almost in a linear way according to the increase of installation of the compact fluorescent lamps. For the purposes of this analysis several scenarios for the extent of the CFL installation extent and the efficiency of the renewable energy sources are considered.

2. Kythnos island energy audit

The island of Kythnos is shown in Fig. 1 and is spotted in West Aegean Sea with more than 2.000 inhabitants. Today, it is supplied mainly by an Autonomous Diesel Station (ADS) of 2MW (5x400kW MWM diesel generators). The high energy cost and the fine weather conditions forced PPC to choose this island for the first large scaled renewable energy sources pilot program. In August 1990 five 33kW Aeroman wind generators and in June 1983 a 100kWp PV power plant consisting of 860 panels of 120W each was installed, occupying an area of 1200m^2. In April 1993 a new-generation line-commutated inverter took the place of the damaged old self-commutated one. Finally, in 2001 the wind farm was enlarged by a 500kW (Vestas V39) wind generator, while an electric energy storage system was also installed, consisted of 200 Hagen batteries.

Fig. 1 Kythnos island

The solid-state device, interfacing the PV system to the AC network, is a 100KW, 3-phase, 6-pulse grid connected thyristor inverter, in a fully controlled 3-phase bridge circuit. An inverter transformer is intended for the adaptation of the inverter output voltage to the grid voltage and for potential separation. The technical characteristics of this inverter are shown in Table 1. Line-commutated inverters switch at the same fundamental frequency as the utility (50Hz). Since the unfiltered current waveforms are rectangular, relative to the utility voltage, they contain many harmonics, particularly the most harmful low order ones (5th and 7th in a standard 6-pulse converter) and the output current must be heavily filtered to reduce this distortion.

Another disadvantage of the line-commutation method is that there is always a delay between the line voltage and the current injected from the DC source. This means that the inverter operates at a lagging power factor, especially at low output (low DC voltage), meaning accordingly that line-commutated inverters consume reactive power. For this reason, the reactive power received by the inverter is getting compensated via stepwise connectable chocked capacitors so that cosφ>0.95 can be kept at nominal power.

The advantage of line-commutation is the simplicity of the control circuitry and the use of thyristors, which are cheap and robust at low frequency applications.

Table 1 Technical characteristics of the 100kW line-commutated inverter

Input Voltage range	130–210V
No-load voltage of the solar generator at 25^{o}C/1sun	200V dc
Maximum MPP voltage at 25^{o}C/1sun	160V dc
Maximum rated DC current	624A
Nominal DC Power	100kW
Output Voltage	3x230/400V +10%-20%
Grid frequency	50+/- 3Hz
cosφ at nominal power	>0.95
DC ripple	<5%
Efficiency at 170 V dc – 100% load	93%
Efficiency at 170 V dc – 75% load	92.5%
Efficiency at 170 V dc – 50% load	92.5%
Efficiency at 170 V dc – 25% load	90%

The inverter input voltage is regulated and controlled by four 25kW DC-DC converters, which convert the 160V dc output of the PV power plant to suitable input voltage for the inverter.

The island network is 3-phase with a nominal voltage of 15kV and frequency 50Hz. The network is not clearly radial 57 voltage transformers (15kV/0.4kV) with rated power 25kVA – 250kVA are connected to it. A simplified diagram showing the topology of the electric network of Kythnos Island is shown in Fig. 2. As far as the loads in Kythnos is concerned, the PPC of Greece suggests gas for cooking, solar panels for hot water and oil heaters for heating in order to minimize the electrical loads. However, Kythnos is a quite large island and PPC can only suggest and not oblige the consumers to use of low consumption appliances, as it happens in Arki and Antikythira, two small islands with weak electric systems and a 20kWp PV power plant each. The most used electrical appliances are incandescent lamps and other low power, home appliances. Load statistical data of the island of Kythnos show that the load profile of each house consists of lighting (50%) and other consuming appliances (50%).

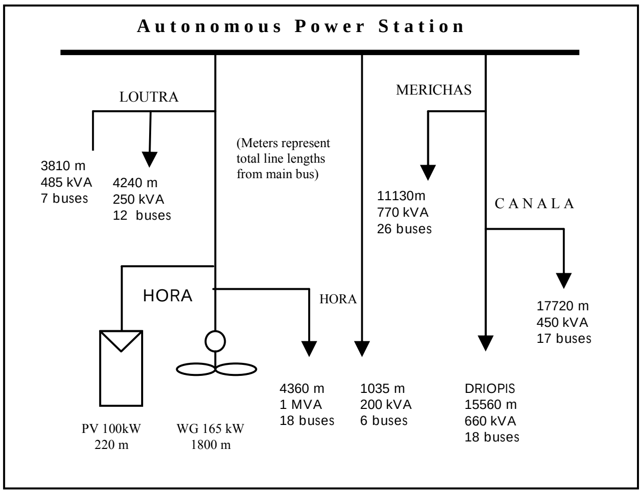

Fig. 2. Topology of the electric network of Kythnos.

In Kythnos network a load-asymmetry between the three phases was observed. Actually, almost 30% of the load is supplied by the S and T phases. This has been taken into account while simulating the load in the 3–phase network. The existing harmonic distortion of the line voltage was also measured at several sites of the island

3. Field measurements

As described above Kythnos island is supplied by a hybrid system consisted of an ADS, a PV and a wind farm. The voltage and current THD measurements were performed after connecting the PV and the wind farm and disconnecting the diesel and vice-versa [10].

The field measurements were performed during July, which means that the solar radiation was very high, thus making the PV station to operate in almost nominal power. Measurements were also performed at numerous pre-selected lines of the electric grid and at houses and other customers as presented in [10]. The measuring instrument was the Dossena Multiver 3S. The measurements were being obtained every 500μsec (2 kHz) 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 (0-950 Hz).

Measurements were performed at the following points of the island network:

- At the output of the PV station
- At the output of the wind farm
- At houses and other customers
- At the output of the 150kV transformer at Hora (main bus): ADS on, PV on
- At the output of the 150kV transformer at Hora (main bus): ADS on, PV off
- At the output of the 150kV transformer at Hora (at 4 departures): ADS on, PV on
- At the output of the 100kV transformer at Hora (main bus): ADS on, PV on
- At the output of the 100kV transformer at Hora (main bus): ADS on, PV off

Given the fact that the PV plant injects harmonics into the grid, it is obvious that the harmonic distortion at the output of the PV station is a very important input data for the purposes of the simulation. The voltage harmonic spectrum at the output of the PV station and the wind farm was recorded during different times and days. The voltage and current THD factors at their output are shown in Table 2. For the determination of the voltage THD the IEEE definition was used:

$$THD_v = \frac{\sqrt{V_2^2 + V_3^2 + ... + V_N^2}}{V_1} \cdot 100$$

where V_1 is the RMS value of the fundamental and V_N the RMS value of the N–order harmonic component.

Table 2 Voltage and current THD factors at the output of the PV station and the wind farm

Phase	THD_V [%]	THD_I [%]
	Output of PV power station	
A	3.937	15.496
B	4.104	15.530
C	3.800	10.946
	Output of wind farm	
A	1.158	3.134
B	1.221	3.169
C	1.162	3.046

After statistical analysis of the measurements the harmonic spectrum that represents most accurately the harmonic voltage and current condition at the output of the PV station is shown in Tables 3 and 4.

The harmonic spectrum measured at the output of the first wind farm is presented in Table 5. The voltage THD values are 1.158% for phase A, 1.221% for phase B and 1.162% for phase C. In addition, the current harmonic components of the wind farm vary from 0.5% to 2.0%.

Table 3 Voltage spectrum at the PV station output

Voltage harmonics at the output of the PV station									
Phase	3rd %	5th %	7th %	9th %	11th %	13th %	15th %	17th %	19th %
A	1.1	1.5	1.5	1.0	1.7	1.2	1.1	1.5	1.0
B	1.4	1.3	1.1	1.3	1.8	1.4	1.3	1.4	1.2
C	1.1	1.4	1.4	1.1	1.7	1.2	1.0	1.4	0.9

Table 4 Current spectrum at the PV station output

Current harmonics at the output of the PV station									
Phase	3rd %	5th %	7th %	9th %	11th %	13th %	15th %	17th %	19th %
A	7.5	10.6	2.7	1.8	4.5	2.9	2.2	4.3	3.0
B	6.1	11.3	2.4	2.0	4.6	3.2	2.6	4.1	3.4
C	1.6	6.3	3.0	1.8	4.8	2.8	2.2	4.4	3.2

Table 5 Voltage spectrum at the output of the first wind farm

Voltage harmonics of the first wind farm									
Phase	3rd %	5th %	7th %	9th %	11th %	13th %	15th %	17th %	19th %
A	0.2	0.5	0.1	0.1	0.5	0.4	0.2	0.7	0.3
B	0.2	0.5	0.3	0.1	0.5	0.4	0.2	0.7	0.4
C	0.2	0.4	0.2	0.1	0.5	0.4	0.2	0.7	0.4

4. Laboratory tests on CFLs

Many samples of CFLs (Philips, Osram, Sylvania) were tested and measured in the NTUA Photometry Lab in order to determine their odd order harmonic spectrum. The use of real and reliable data is a necessary step for a precise simulation. The measurement of the exact current harmonic content of these CFLs is presented in Table 6. 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 rated between 15W 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 (~0.6) due to the considerable harmonic content of current.

Table 6 Amplitude of CFL current harmonics

CFL type	3rd %	5th %	7th %	9th %	11th %	13th %	15th %	17th %	19th %	21st %	THD_I [%]
15W	86	56	40	34	24	14	12	9	7	7	121.07
20W	92	72	53	45	43	40	33	25	21	18	158.02
23W	93	70	54	49	46	38	30	25	22	19	159.44

It is obvious that for all lamps all harmonic components are very high and especially the 3rd and the 5th are close to the fundamental, a fact that can lead to significant distortion of the voltage, if the installed power of CFLs is high. As a result, the power factor is very low as shown in Table 7. The reactive power absorbed by CFLs is low, but most of the consumed power is used by harmonic components.

Table 7 Measured power parameters of tested CFLs

CFL type	P (W)	Q (VAr)	D (VA)	S (VA)	P.F.
15W	13.96	4.59	24.99	28.99	0.480
20W	19.50	7.02	31.94	38.07	0.510
23W	22.02	8.93	36.32	43.40	0.510

All data from the measurements and the energy audit are properly used as input in the simulation model in order to estimate the influence of CFLs to the network voltage distortion.

5. Simulation

For the purposes of the simulation the PSCAD v3.0.6 software was used. Every part of the network was simulated with the best possible accuracy. Apart from the field measurements, any other part of the network that is involved with the harmonic power flow has been taken into account in the simulation procedure.

Transformers: Kythnos electric network is consisted of 57 distribution transformers medium to low voltage. Their nominal power is rated from 25 to 250kVA. In PSCAD software there is a pre-designed transformer model. No equivalent circuit was used. In this model data as the transformer nominal power, the per unit shunt resistance, transformation ratios and the connection type used for every transformer (usually ΔYn11), were taken into account. Table 8 presents the electrical characteristics of the transformers.

Table 8 Electrical characteristics of Kythnos transformers

Nominal Power (kVA)	Trans. ratios (kV)	R_M (mOhm)	X_M (mOhm)	Z_M (p.u.)
25	20/0.4	175	228	0.0449
50	20/0.4	75	122	0.0448
100	20/0.4	29	65.5	0.0448
150	20/0.4	18.3	44.5	0.0451
200	20/0.4	13.4	33.5	0.0451
250	20/0.4	10.5	26.8	0.0450

Distribution lines: Power is distributed to the loads via 5 different types of overhead lines, as described in detail in Table 9. For the simulation of the lines their resistance and impedance are used.

Table 9 Technical characteristics of Kythnos medium voltage overhead lines

	Line type	R (Ohm/km)	X (ohm/km)
1	ACSR 3x16	1.317	0.821
2	AAAC 3x35	1.120	0.801
3	Cu 3x16	1.323	0.824
4	Cu 3x35	0.645	0.800
5	Cu 3x95	0.269	0.765

Renewable energy sources: As described, the PV station of Kythnos injects significant amount of harmonic distortion in the network. In order to simulate this non linear behaviour the voltage harmonic components at the output of the PV station are used, as presented in Table 3. For the wind farm the information of Table 5 is used. All harmonic values are converted to voltage & current rms values. Finally, the characteristics (P, Q, cosφ, V_{n1}, φ_{n1}, I_{n1}, φ_{In1}) of every fundamental system are estimated.

CFLs: The examined network is initially considered to use mostly incandescent lamps. In order to proceed to the gradual substitution of these lamps to CFLs, the 20W CFL is considered equivalent to the 75W incandescent lamp. While all incandescent lamps are purely resistive loads, CFLs are highly non linear loads and their harmonic behaviour has to be simulated considering the rms values of the harmonic current components of one CFL that are injected into the network, as shown in Table 10.

Table 10 Current spectrum of a typical CFL 20W

Current harmonics (mA) of CFL 20W									
I_{n1}	I_{n3}	I_{n5}	I_{n7}	I_{n9}	I_{n11}	I_{n13}	I_{n15}	I_{n17}	I_{n19}
90	80	64	44	26	17	15	11.3	6.1	2.3

Load: The total nominal power of the transformers of Kythnos network is 4380KVA. It is considered that at the moment of the simulation all transformers have the same load coefficient. A typical day load curve of Kythnos island is shown in Fig.3. This curve is a typical day of May 2002. It seems interesting to examine the network during the night peak. At this peak the load is high, while lighting is a significant part of it. In order to estimate the extent of lighting in the total load it is assumed that initially lighting is covered by incandescent lamps. Then we accept that 70% of the load is for residential use, 20% for commercial and 10% for other uses. According to statistical data lighting represent the 8% of the installed residential load and the 24,7% of the installed commercial load.

The decrease of installed power for lighting due to the substitution of the incandescent lamps with CFLs is taken into account in the simulation. The total power of every transformer is then changed because a the considerable amount of the active power of incandescent lamps no longer exits, while active and reactive power of CFLs is added.

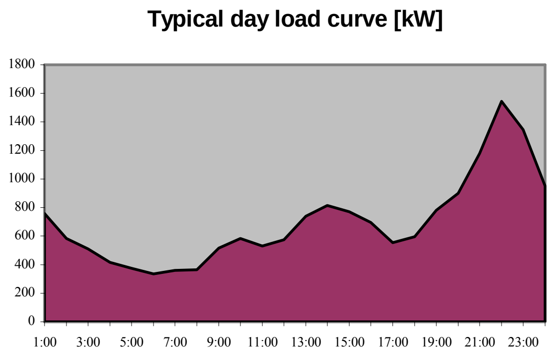

Fig. 3 Typical day load curve of Kythnos island.

6. Results and discussion

For the purposes of this research 8 different scenarios were examined during the simulation procedure. The aim of the simulation is to determine the extent of the harmonic distortion caused by the Renewable Energy Sources (RES) installed and by the substitution of incandescent lamps with CFLs. Through the first three scenarios the extent of harmonic distortion due to RES operation was estimated. Through the next 5 simulation scenarios the harmonic distortion caused by the large scale CFLs installation was estimated. These scenarios assumed that there is a harmonic voltage distortion in the network already. Using PSCAD software the voltage and current THD, the harmonic components and the harmonic phases of 10 transformers at both their medium and low voltage side were measured. The 8 scenarios and the main conclusions that were drawn are the following:

- 1st scenario: Operation of the ADS and the wind farm before the installation of CFLs.
- 2nd scenario: Operation of the ADS and the PV station before the installation of CFLs.
- 3rd scenario: Operation of the ADS and the wind farm & PV Station before the installation of CFLs.
- 4th scenario: Substitution of 25% of incandescent lamps with CFLs with electronic gear in combination with the operation of the ADS and the wind farm.
- 5th scenario: Substitution of 50% of incandescent lamps with CFLs with electronic gear in combination with the operation of the ADS and the wind farm.
- 6th scenario: Substitution of 75% of incandescent lamps with CFLs with electronic gear in combination with the operation of the ADS and the wind farm.
- 7th scenario: Substitution of 90% of incandescent lamps with CFLs with electronic gear in combination with the operation of the ADS and the wind farm.
- 8th scenario: Substitution of 90% of incandescent lamps with CFLs with electronic gear in combination with the operation of the ADS, the wind farm and the PV station.

From the analysis of the scenarios 1, 2 and 3, it was observed that the harmonic distortion cause by the RES was very low. The wind farm caused negligible voltage THD, the PV station not more than 0.5% throughout the network, while in simultaneous operation the THD_V did not reach any further values.

From the analysis of the scenarios 4, 5, 6 and 7, it became clear that the harmonic distortion caused in the network is due to the influence of CFLs and it is proportional to the total installed power of these lamps. It was found that the voltage THD did not exceed in any of the examined scenarios the limit of 5%. More specifically, maximum THD_V varied from 0.8% (4th scenario) to 3.03% (7th scenario). In the 8th scenario THD_V did not exceeded 3.03%.

Maximum values occurred at transformers remote from the ADS. THD_V was found to be higher at low voltage side than at medium voltage side. In Table 11 the THD_V values for all scenarios of CFL installation in low and medium voltage at all phases are presented. These values refer to transformer No 38, the bus of which showed maximum distortion values.

Table 11 Voltage THD in low and medium voltage network for all scenarios of CFL installation

Total harmonic distortion of voltage (%)			
CFL installation scenario	Phase	Low Voltage	High Voltage
0%CFL-100%INC	a	0.07671	0.08165
	b	0.07807	0.08114
	c	0.07592	0.07948
25%CFL-75%INC	a	0.77810	0.36350
	b	0.80000	0.37400
	c	0.81700	0.36640
50%CFL-50%INC	a	1.54900	0.68560
	b	1.58800	0.70160
	c	1.62200	0.68870
75%CFL-25%INC	a	2.33700	1.02200
	b	2.37100	1.04100
	c	2,49100	1.05600
90%CFL-10%INC	a	2.89000	1.33000
	b	2.95600	1.34800
	c	3.03300	1.35400

As expected, all harmonic components are increased when CFLs installation extent is also increased. When this extent reaches 75% or 90% the 15th voltage harmonic component exceeds the allowed limit (0.3%) according to standard IEC 61000-3-6. Harmonic components 5th and 7th have the highest values among the other components, while 17th and 19th the lowest. The same increase is observed in current harmonic components and in current THD, which varied between 0.02% - 23.67%. In Table 12 the THD_I values for all different scenarios of CFLs installation in low and medium voltage at all phases are presented. These values refer again to transformer No 38.

Table 12 Current THD in low and medium voltage network for all scenarios of CFL installation

Total harmonic distortion of current (%)			
CFL installation scenario	Phase	Low Voltage	High Voltage
0%CFL-100%INC	a	0.02404	0.02425
	b	0.02436	0.02375
	c	0.02303	0.02342
25%CFL-75%INC	a	4.95000	3.17000
	b	4.96300	3.17500
	c	4.96600	3.16400
50%CFL-50%INC	a	11.02000	6.94800
	b	11.03000	6.96500
	c	11.03000	6.95300
75%CFL-25%INC	a	18.40000	11.49000
	b	18.38000	11.52000
	c	18.38000	11.49000
90%CFL-10%INC	a	23.67000	14.49000
	b	23.63000	14.52000
	c	23.62000	14.48000

Finally, the power factor at the load of distribution transformers for all scenarios is examined. It is observed that the power factor and the displacement factor decrease when CFLs extent increases. The values of power factor and the displacement factor at the transformer No 56 for the fundamental system are shown in Table 13. For the worse scenario of 90% substitution of incandescent lamps with CFLs power factor is about 0.84 and displacement factor 0.86.

7. Conclusions

The harmonic distortion problem is a complex one, especially in small size electric networks, where Renewable Energy Sources are installed. Because the power quality is affected by non-linear loads, every significant change of load synthesis to achieve energy saving must be thoroughly studied. The use of energy saving technologies (e.g. CFLs) in order to decrease the power consumption in such networks may result in unacceptable distortions in the network line voltage. An important parameter for energy saving strategies is the use of CFLs with electronic gear.

Table 13 Power factor and displacement factor values

Power factor estimation at transformer No 56						
Scenario	P (kW)	Q (kVAr)	D (kVA)	S (kVA)	P.F.	$\cos\varphi_{n1}$
0% CFL	91.06	29.91	0.00	95.84	0.9500	0.9500
25% CFL	80.52	30.71	4.49	86.29	0.9331	0.9343
50% CFL	71.29	31.86	9.00	78.60	0.9070	0.9125
75% CFL	62.29	33.06	13.57	71.81	0.8674	0.8821
90% CFL	57.10	33.84	16.38	68.36	0.8352	0.8583

In order to examine the consequences caused to the harmonic distortion of a network supplied by a hybrid system (ADS, wind farm and PV station) due to a possible extended use of compact fluorescent lamps (CFLs) with electronic gear, Kythnos network was chosen for analysis. After a detailed simulation of the 3-phase medium voltage network of Kythnos Island under different CFLs installation scenarios, it was shown that the harmonic distortion by the renewable energy sources is negligible, while the harmonic distortion caused by the use of compact fluorescent lamps is considerably higher and increases almost linearly with the increase of installation of the CFLs.

Total harmonic distortion of voltage (THD_V) in all scenarios studied was under the permitted limits. More specifically, maximum THD_V varied from 0.8% (4th scenario) to 3.03% (7th scenario). The 15th voltage harmonic was found to exceed the permitted limit, according to IEC 61000-3-6, only in the scenarios with a great replacement of incandescent lamps with CFLs. It is recommended that CFLs installation should be decided up to the point that the distortion caused does not exceed international set limits. The optimum level of replacement can be determined to the point where the cost of power quality improvement is smaller than the gain in energy saving.

Acknowledgment: The project is co - funded by the European Social Fund (75%) and National Resources (25%) - Operational Program for Educational and Vocational Training II (EPEAEK II) and particularly the Program PYTHAGORAS II.

References:

[1] IEC 61000-3-6, “Electromagnetic compatibility (EMC) – Part 3: Limits – Section 6: Assessment of emission limits for distorting loads in MV and HV power systems”, 1996

[2] EN 50160, “Voltage characteristics of electricity supplied by public distribution networks”, 2000

[3] IEEE Working group on power system harmonics, "Power system harmonics - An overview", *IEEE Trans. PAS*, 102(8), 1983.

[4] J. Arrillaga, D.A. Bradley, P.S. Bodgen, *Power system harmonics* (John Wiley & Sons, London, 1985).

[5] IEEE Committee Report, "The effects of power system harmonics on power system equipment and loads", *IEEE Trans. PAS*, 104(9), 1985.

[6] G. Vokas, S. Kaminaris, A. Androutsos, J. Souflis, A. Machias, V.Papadias, "Electric grid problems analysis caused by interconnected PV stations", Oct.1992, *4th Conf. of Solar Technique Institute*, Xanthi, Greece.

[7] S.A. Papathanasiou, G.A. Vokas, M.P. Papadopoulos, "Use of power electronic converters in wind and photovoltaic generators", July 10-14 1995 *IEEE International Symposium on Industrial Electronics ISIE'95*, Athens - Greece.

[8] P.N. Enjeti, P.D. Ziogas, J.F. Lindsay, "Programmed PWM techniques to eliminate harmonics: a critical evaluation", *IEEE Trans. Industry Applications*, 26(2), 1990.

[9] M. Tortoreli, P. Baltas, G.A. Vokas, A.V. Machias, "Photovoltaic induced harmonic power distortion in the Kythnos island: Field measurements and analysis", April 1994, *International Solar Conference*, The Nederlands.

[10] G.A. Vokas, A.V. Machias, "Harmonic voltages and currents on two Greek islands with photovoltaic stations: Study and field measurements", *IEEE Trans. Energy Conversion*, 10(2), 1995.

[11] M.H. Rashid, *Power Electronics Circuits Devices and Applications"* (Prendice-Hall International Editions, 1988).

[12] E.F. Ruchs, D.I. Roesler, K.P. Koracs, "Sensitivity of electrical appliances to harmonics and fractional harmonics of the power systems voltage-Part I: Television sets, induction Watthour meters and universal machines", *IEEE Trans. Power Delivery*, 2(2), 1987.

[13] G.A. Vokas, I.F.Gonos, F.N.Korovesis, F.V. Topalis, “Influence of compact fluorescent lamps on the power quality of weak low-voltage networks supplied by autonomous photovoltaic stations”, PowerTech’2001, Porto, Portugal, September, 2001, 10-13.

[14] M. Etezadi-Amoli, T. Florence, “Power factor and harmonic distortion characteristics of energy efficient lamps”, *IEEE Trans. on Power Delivery*, 4(3), 1989.

[15] F.V. Topalis, Efficiency of energy saving lamps and harmonic distortion in distribution systems, *IEEE Trans. Power Delivery,* 8(4), 1993, 2038-2042.

[16] F.V. Topalis, I.F. Gonos, G.A. Vokas, “Arbitrary waveform generator for harmonic distortion tests on compact fluorescent lamps”, *Measurement*, 30(4), 2001, 257-267.

[17] R.R. Verderber, O.C. Morse, W.R. Alling, Harmonics from compact fluorescent lamps, *IEEE Trans. Industry Applications*, 29(3), 1993, 670-674.

[18] P.N. Korovesis, G.A. Vokas, I.F. Gonos, F.V. Topalis, “Influence of large scale Installation of energy saving lamps on the line voltage distortion of a weak network supplied by photovoltaic station”, *IEEE Trans. Power Delivery*, 19(4), 2004.

[19] D.G. Pileggi, E.M. Gulachenski, C.E. Root, T.J. Gentile, A.E. Emanuel, The effect of modern compact fluorescent lights on voltage distortion, *IEEE Trans. Power Delivery,* 8(3), 1993, 1451-1459.

[20] Ming-Tong Chen, Che-Ming Fu, Characteristics of fluorescent lamps under abnormal system voltage conditions, *Electric Power Systems Research*, 41, 1997, 99-107.