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Influence of compact fluorescent lamps on the power quality of weak low-voltage networks supplied by autonomous photovoltaic stations

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***Abstract*– The principal goal of this research is to determine the influence of compact fluorescent lamps (CFLs) harmonics on the voltage distortion of a weak electric network supplied by an autonomous photovoltaic (PV) station. The total harmonic distortion factor at all points of the electric network must be under 5%. The power electronics of a PV station and other highly non-linear loads such as CFLs induce undesirable harmonic components and cause serious problems at the network power quality. For that reason, a specific methodology is developed, which 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. Then, after simulating the whole network, a harmonic flow analysis takes place showing the extent that CFLs influence the power quality. The conclusions drawn from this analysis are important and must be taken into account in every electric network design.**

***Index terms*- Compact fluorescent lamps, Harmonics, Harmonic distortion, Power quality, Photovoltaics.**

I. INTRODUCTION

The problem of grid circulating harmonics was always of great importance. The obligations of the energy producing companies for better energy quality (stable frequency and voltage, high power quality, "clean" waveforms) are increased. 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 [1-5].

The increased use of power electronics (converters, inverters) is also an important harmonic source [2,3,6,11]. 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). In [7,10] it was proved that in all islands the harmonic content of the voltage waveform at points of the electric network was richer in harmonics when the PV station was on rather than when the Diesel generator did supply the system.

The techniques used for the elimination of these harmonics are many and they are applied successfully in most cases in the modern Photovoltaic Systems.

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Such techniques are the SPWM, MPWM and some conventional ones like filtering and specific transformer connections [2,8,9]. Already installed autonomous PV systems in small size low voltage networks (e.g. island of Arki in Greece) use mainly conventional harmonics reduction techniques and at the output of the PV station a relatively high (2,5-4,5%) Voltage Total Harmonic Distortion (THD_V) is present. However, sometimes THD exceeds 5% (above the internationally acceptable THD limits). Non-linear loads (motors, refrigerators, compact fluorescent lamps, 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].

Compact fluorescent lamps (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 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% [14], a fact that causes serious consequences to the customer side.

A large number of papers were published dealing with the harmonic content of CFLs or the behaviour of CFLs under various exploitation conditions i.e. under various voltage distortions and different rms values of the network voltage [15-19]. On the contrary, a small number of analyses is published dealing with the influence of CFLs to the power network wherein they are, i.e. trying to establish their maximal presence without leading to excessive voltage distortion [20, 21].

The principal goal of this research is to determine the influence of CFL harmonics on the voltage distortion of a weak electric network supplied by an autonomous photovoltaic station. 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. Then, after simulating the whole network, a harmonic power flow analysis takes place showing the extent that CFLs influence the power quality.

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II. DESCRIPTION OF THE INSTALLED PV STATION

Arki is a small island of East-Aegean Sea, whose population reaches 100 inhabitants. Its installed PV power is 25 kWp. The whole PV power plant 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 26 Wp [22].

A three-phase static inverter serves the purpose to feed a.c. consumers that require 230V / 400V three-phase a.c. input supply voltage. The d.c. input supply voltage for the static inverter is taken from the d.c. mains supply system (PV Array). The PV station of the island is equipped with the inverter model: AEG - "G 220 D 400/43/2 rgf - V30", self-commutated inverter. The DC input supply voltage inverter is 220 V, (+/-15%), the Rated AC voltage is 3x400 V (full load neutral) and the Rated Power at cosφ = 1 is 24 kW. Its efficiency under normal conditions is more than 86% [23, 24].

The power electronic section consists of six thyristor stacks combined into two six-pulse three-phase full-wave bridge circuits. That means that each three out of the six identically assembled low-loss McMurray circuits form a three-phase full- wave bridge circuit configuration. With corresponding periodic sequence of triggering the main thyristors, each three-phase full- wave bridge circuit supplies a separate three-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 system but both ending at a common secondary winding [23].

III. FIELD DISTORTION MEASUREMENTS AT THE ARKI PV STATION

As mentioned before, the customers of the island of Arki can be supplied either by the PV station or by the Diesel station, which operates only in emergency cases (too many cloudy days, PV station service etc). In [7] it was proved 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. This harmonic content is a very important input data for the simulation.

The THD according to IEEE definition is:

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

where V_1 is the root-mean square of the fundamental voltage waveform and V_N the root-mean square of the N-order harmonic of voltage waveform.

The produced voltage waveform condition was identified and measured before the filters and at the output of the whole PV station. Measurements were also performed at numerous preselected lines along the electric grid and at houses and other customers as presented in [7]. The measuring instrument was the Multiver 3S of Dossena. The measurements were being obtained every 500 microsec (2kHz) in each sample procedure. Each sample contains 3 voltage and 4 current "sub-samples". The final analysis of the samples was carried out using the method of Fast Fourier Transform. The corresponding software for the computational analysis and calculation of the obtained samples was analysing harmonics up to the 19th order (0-1000 Hz). The comparison between the produced voltage waveform before filters to the one at the output of the whole PV station is presented in Fig. 1.

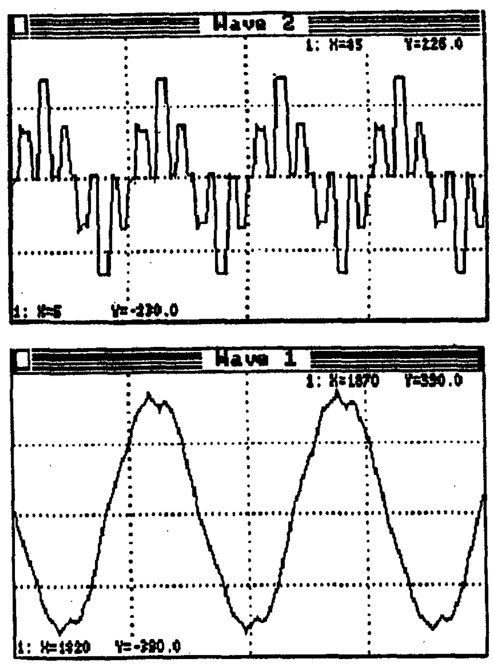

Fig. 1. Arki - The produced voltage waveform: a) before the filters and b) at the output of the PV station

As shown in Fig. 1 filters and other control techniques have efficiently reduced the harmonic distortion at the output of the PV station. In Fig. 2 the harmonic spectrums of two cases are presented. Case 'A' is one of the most distorted (THD: 4,43%), while case 'B' is one of the less distorted ones (THD: 3,14%). Case 'B' is considered to be the input data of the voltage harmonic spectrum that the PV station produces in our simulation.

	3rd	5th	7th	9th	11th	13th	15th	17th	19th
□A (%)	1,6	3,4	0,4	0,1	1,4	1,8	0,3	0,3	0,1
■B (%)	0,9	2,2	0,3	0,1	1,3	1,8	0,3	0,3	0

Fig. 2. Arki - Harmonic spectrums of the voltage waveform at the output of the PV station.

At the island of Arki the voltage THD at different places if the electric grid was measured to be 1.85% - 5.30% [7]. 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, 7]. This fact proves how weak and sensitive is the local network under possible nonlinear loads. However, the International Electrotechnical Commission (IEC) in IEC 61000-3-2 has suggested limits for the current distortion caused by household appliances and similar electrical equipment [25].

The nominal power of the CFLs that are widely used in the households of the island is 20 W and 23 W. These lamps replace the incandescent ones of 75 W and 100 W respectively. Many samples of CFLs were tested in the laboratory in order to determine their harmonic spectrum. The measurements were performed with the same apparatus that was used for the field measurements of the PV system. 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 CFLs is presented in Table I.

TABLE I

NORMALISED AMPLITUDE (%) OF CFL HARMONICS.

Harmonics	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**

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.

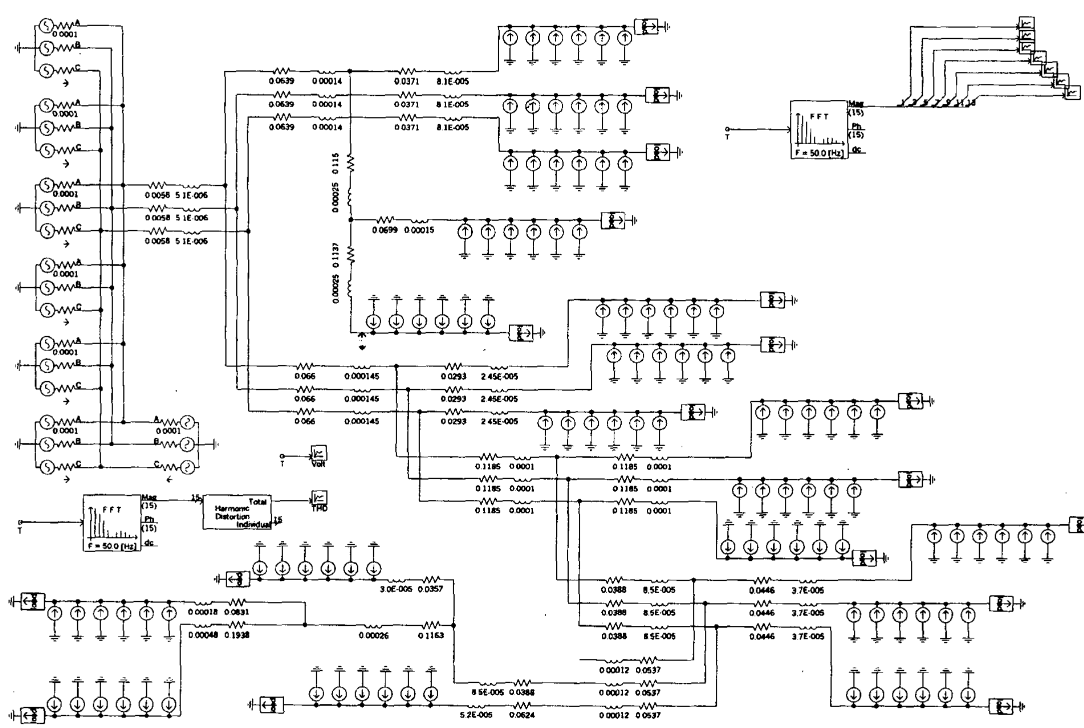

Fig. 3. The electric network of Arki (the current sources represent the harmonic content of CFLs)

IV. SIMULATION

The island's network supplies 60 houses. Due to the low installed power of the inverter (30kVA), no high energy demanding electrical appliances are allowed. Public Power Corporation 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.

According to field measurements the typical house average consumption was found to be 100 – 400 W under normal (no-peak) conditions. Then, taking into consideration the statistical data of the load of the island of Arki one comes to the conclusion that the load profile consists of 50% in lighting and 50% in the rest consuming appliances.

The scenario considered for simulation includes three house categories.

The first house category (low power) consists of one incandescent lamp of 100W and other load types of 100W in total. The power factor in this case is 0,78.

The second one (medium power) consists of two incandescent lamps of 75W and other load types of 150W in total. The power factor in this case is 0,85.

The third one (high power) consists of two incandescent lamps of 100W and other load types of 200W in total. The power factor in this case is 0,87.

For the electric network simulation the PSCAD v3.0.6 software is used. The network cables 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 scenario examines the voltage harmonic distortion at all network buses assuming that all incandescent lamps are replaced with CFLs.

The 100W incandescent lamp is replaced with a 23W CFL and the 75W incandescent lamp is replaced with a 20W CFL. In both cases laboratory measurements showed that each lamp of a pair has the same maintained luminous flux with the other one.

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 behavior 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 I. Even harmonic currents are not produced by such lamps. The odd order harmonic current amplitude is measured in the laboratory. The highest harmonic order is the 13th since the contribution of the others (15th, 17th, etc) is nearly negligible. On the other hand the network then becomes quite complicated.

Initially the electric network was analysed only with linear loads, while as inverter THD factor was considered one of the less distorted ones (3,14%). This is the most favorable 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 the scenario of the replacement of incandescent lamps with CFLs was analysed. The electric network of Arki, after the addition of the harmonic current of CFLs is fully described in Fig. 3. The calculation results in Table II show that replacing incandescent lamps to CFLs the THD of some buses is more than 4,5%.

Given that the rest loads of the network were considered linear (which is not true) one comes to the conclusion that the voltage THD factor of 4,5% is the least possibly expected, when replacing incandescent lamps to CFLs according to the above described scenario. This also means that even in that ideal scenario CFLs increase the voltage THD factor near to the acceptable limits of 5%. So, in the real electric network, where non-linear loads are present (refrigerators, TV sets, etc), the voltage THD factor will possibly exceed the acceptable limit of 5%.

TABLE II
NORMALISED AMPLITUDE (%) OF VOLTAGE HARMONICS AT ALL ELECTRIC NETWORK BUSES

Bus	3^{rd} (%)	5^{th} (%)	7^{th} (%)	9^{th} (%)	11^{th} (%)	13^{th} (%)	THD
1T	0.90	2.20	0.30	0.10	1.30	1.78	3.253
1S	0.90	2.20	0.30	0.10	1.30	1.78	3.258
1R	0.90	2.20	0.30	0.10	1.30	1.78	3.254
2T	0.92	2.22	0.31	0.11	1.30	1.78	3.278
2S	0.87	2.17	0.29	0.09	1.28	1.76	3.209
2R	0.90	2.21	0.31	0.11	1.30	1.79	3.267
3T	1.04	2.32	0.46	0.26	1.33	1.81	3.432
3S	0.27	1.45	0.10	0.44	0.91	1.37	2.255
3R	1.13	2.51	0.51	0.39	1.49	1.98	3.76
4T	1.06	2.33	0.48	0.27	1.33	1.81	3.453
4S	0.26	1.43	0.09	0.45	0.90	1.36	2.233
4R	1.14	2.52	0.52	0.39	1.49	1.98	3.77
5T	1.18	2.49	0.60	0.36	1.36	1.84	3.612
5S	0.28	0.91	0.09	0.77	0.67	1.12	1.785
5R	1.28	2.68	0.63	0.57	1.60	2.09	4.06
6T	1.25	2.50	0.66	0.41	1.38	1.85	3.709
6S	0.32	0.86	0.11	0.79	0.65	1.10	1.765
6R	1.33	2.73	0.69	0.62	1.63	2.12	4.147
7T	1.21	2.46	0.64	0.40	1.37	1.84	3.659
7S	0.53	0.58	0.14	1.01	0.53	0.95	1.686
7R	1.40	2.82	0.69	0.69	1.68	2.17	4.288
8T	1.24	2.49	0.67	0.42	1.38	1.85	3.696
8S	0.54	0.56	0.15	1.02	0.53	0.94	1.687
8R	1.42	2.84	0.71	0.70	1.69	2.18	4.321
9T	1.21	2.46	0.64	0.40	1.37	1.84	3.659
9S	0.89	0.31	0.18	1.33	0.43	0.77	1.862
9R	1.51	2.95	0.70	0.80	1.75	2.25	4.502
10R	1.57	3.01	0.71	0.84	1.78	2.28	4.591
11S	1.15	0.43	0.21	1.56	0.44	0.68	2.157
12S	1.20	0.46	0.21	1.59	0.44	0.67	2.203
13S	1.69	1.03	0.27	2.03	0.65	0.66	2.996
14S	1.88	1.26	0.29	2.19	0.76	0.71	3.331
15S	2.18	1.65	0.33	2.46	0.95	0.83	3.903
16T	1.13	2.39	0.36	0.37	1.35	1.83	3.524
16S	0.80	2.08	0.21	0.03	1.23	1.71	3.078
16R	0.93	2.24	0.34	0.14	1.32	1.81	3.32
17T	1.16	2.41	0.39	0.40	1.36	1.83	3.566
17S	0.76	2.03	0.17	0.04	1.21	1.69	3.005
17R	0.94	2.26	0.36	0.15	1.33	1.82	3.352
18T	1.54	2.74	0.39	0.81	1.50	1.94	4.088
19T	1.68	2.87	0.41	0.94	1.55	1.99	4.295
20T	1.77	2.96	0.41	1.03	1.59	2.02	4.439

V. 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, the 100% replacement of the incandescent lamps with CFLs may lead to unacceptable values of THD (>5%), taken also into account the existence of other non-linear loads.

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.

VI. REFERENCES

[1] IEEE Working Group on Power System Harmonics, "Power System Harmonics - An Overview", *IEEE Trans.PAS*, Vol.PAS-102, No.8, August 1983.

[2] J. Arrillaga, D.A. Bradley, P.S. Bodgen, *Power System Harmonics*, John Wiley & Sons, London, 1985.

[3] R. Barnes, "Harmonics in Power Systems", *Power Engineering Journal*, pp.11-15, 1989.

[4] IEEE Committe Report, "The effects of Power System Harmonics on Power System Equipment and Loads", *IEEE Trans.on PAS*, Vol.PAS-104, No.9, 1985.

[5] J. Subjak, J. McQuilkin, "Harmonics-Causes, Effects, Measurements, Analysis: An Update", *IEEE on IA*, Vol.26, No.6, December 1990.

[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] G.A. Vokas, A.V. Machias, "Harmonic Voltages and Currents on two Greek Islands with Photovoltaic Stations: Study and Field Measurements", *IEEE Trans. on Energy Conversion*, Vol. 10, No.2, June 1995.

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

[9] P.N. Enjeti, P.D. Ziogas, J.F. Lindsay, "Programmed PWM Techniques to Eliminate Harmonics : a Critical Evaluation", *IEEE Trans. on Industry Applications*, Vol.26, No.2, March/April 1990.

[10] 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.

[11] 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.

[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. on Power Delivery*, Vol.PWRD-2, No.2, April 1987.

[13] E.F. Ruchs, D.I. Roesler, K.P. Koracs, "Sensitivity of Electrical Appliances to Harmonics and Fractional Harmonics of the Power Systems Voltage-Part II: Transformers and Induction Machines", *IEEE Trans. on Power Delivery*, Vol.PWRD-2, No.2, April 1987.

[14] C.K. Duffey, R.D. Stratford, "Update of Harmonic Standard IEEE-519: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", *IEEE Trans.IA*, Vol.25, No.6, 1989.

[15] F.V. Topalis, Efficiency of energy saving lamps and harmonic distortion in distribution systems, *IEEE Transactions on Power Delivery*, Vol.PWRD- 8, No.4, pp. 2038-2042, 1993.

[16] M. Etezadi-Amoli, T. Florence, "Power Factor and Harmonic Distortion Characteristics of Energy Efficient Lamps", *IEEE Trans. on Power Delivery*, Vol. 4, No. 3, July 1989.

[17] F.V. Topalis, I.F. Gonos, G.A. Vokas, "Arbitrary waveform generator for harmonic distortion tests on compact fluorescent lamps", *Journal of the International Measurement Confederation*, to be published (2001).

[18] R.R. Verderber, O.C. Morse, W.R. Alling, Harmonics from compact fluorescent lamps, *IEEE Transactions on Industry Applications*, Vol.29, No.3, pp.670-674, 1993.

[19] R. Wolsey, Lighting Answers: Power quality, Lighting Research Center, Rensselaer Polytechnic Institute, 2 (2), February, 1995.

[20] 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 Transactions on Power Delivery* Vol. 8, No.3, pp. 1451-1459, 1993.

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

[22] J. Chadjivassiliadis, G. Betzios, "Arki solar photovoltaic power plant", Public Power Corporation/ Alternative Energy Forms, Greece and J.Wille, Tractebel, Belgium.

[23] AEG, "Equipment Documentation, Description & Operating Instructions for Self Commutated Three- Phase Static Inverters".

[24] M. Clewing, "Kommutierungsvorgaenge in Selbstgefuerhten Wechselrichten", *Techn. Mitt. AEG - Telefunken*, 67 (1977) 1, pp. 61-65.

[25] International Electrotechnical Commission: *Electromagnetic compatibility (EMC): Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase) - Definitions*, IEC 61000-3-2 (2000-08), Geneve, Switzerland, 2000.

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