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Modeling and Measurement of Small Photovoltaic Systems and Penetration Scenarios

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***Abstract*-- The operation of Photovoltaic (PV) units connected to the system is characterized by several uncertainties due to the number of running units, the points where these units are sited, the exported power and the injection of harmonic currents. The objective of this paper is to investigate the penetration level of PV units in the low voltage (LV) network. Starting from field measurements a model has been created for the computation of harmonics and voltages in the grid. The PV unit is modeled as a dc voltage source connected to the network via electronic switches, representing the PV inverter. Simulations were performed in the simulator packages PSIM© and Harmoniques©. Results from the simulated model agree with the results obtained by the measurement campaign. Following this the acceptable penetration level of PV systems in the LV distribution network is investigated for several scenarios, referring the number, the locations and the operation of the units.**

***Index Terms*-- Distributed energy sources, Photovoltaic power systems, Power distribution, Power system harmonics.**

I. Introduction

THE use of PV systems is continuously increasing as a result of active government policies for renewable energy sources. As PV systems incorporate power conditioning units which are harmonic generating devices, much concern on the current and voltage distortion arouses. From the harmonic distortion and voltage stability standpoint, issues that arise from the potential use of PV generation are as follows:

1) The harmonic behavior of these distributed resources and their relation with the weather variations and the nominal output current of the PV system.

2) The acceptable penetration level of PV systems in the LV distribution network without harmonic and voltage limits been exceeded, as defined in the standards EN 50160 [1] and IEEE 1547 [2].

The above issues are related to the waveform distortion caused by the power electronics used for the connection of the PV unit to the grid and they are a subject of investigation in many papers [3] - [8]. The harmonic impact of PV systems is a result of many stochastic parameters. It is agreed that the behavior of DG is much dependant on the grid impedance, especially when the grid contains non linear loads, changeable during the day and that causes harmonic currents with variable amplitudes and phase angles [9] - [11]. Thus the injected current of inverters is related to the voltage harmonics present on the grid.

This paper reviews the results from measurement campaigns performed during several days of October 2007 in a 20 kWp PV plant in Korinos (in the prefecture of Pieria, Northern Greece). During the field experiment the PV station was put out of operation for 20 min, in order to track and register the harmonic background of the network.

The harmonic profile of the PV system and the network, containing the amplitude and the angle shift of current harmonics, is registered with the use of a data acquisition system. A model of the network is suggested in this paper, by simulating its harmonic components using current sources, as presented in many studies [12], [13] and then models the PV inverters with controller switches. The results of the connection of the PV system in the network is being examined and compared to those obtained by the test field. The investigation continues with the connection of more than one PV system in the same network in different locations or/and in parallel with the first one and the allowable penetration level is discussed. Finally, the behavior of harmonic components for various operation modes of the PV inverters is examined [14].

II. Description of the Measurement Campaign

A. Description of the site

The PV station studied in this work is a 20 kWp system situated in Korinos, Northern Greece. The station is a new installation operating since summer 2007 and is directly connected to the LV distribution system. It consists of 3 couple of strings. Each couple has a string of 18 and a string of 19 panels and is connected to a 5 kW single phase inverter. The inverters are then connected via the electrical switchboard to the LV grid of 230/400 V.

B. Efficiency of the PV plant

The PV station's measurement survey captured a variety of cases during several days of October 2007. During that period, the light part of the day lasted from about 7:00 to 19:00. Under normal conditions the solar radiation curve was symmetrical, reaching a maximum up to 1200 W/m^2 at about 12:00 to 13:00.

For efficiency reasons the PV station has 3 single-phase inverters of 5 kW each, thus it may reach a maximum power output of 15 kW for a solar radiation of about 900-

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1000 W/m^2. For values up to 1000 W/m^2 the output power is linearly related to solar radiation with an efficiency of about 11-12% ($P_{electr.}/P_{solar}$). A diagram of the output power (in kW) vs. solar radiation (in W/m^2) is presented in Fig. 1. The scattered values are due to the fact that the measurement of the solar radiation and the output power were not fully synchronized and some days were partly cloudy.

Daily curves of output power of the PV plant and solar radiation showed that the power generated follows the solar variations. Measurements showed that even short interruptions of small passing clouds may cause sudden dips of output power down to 25% within 3 min.

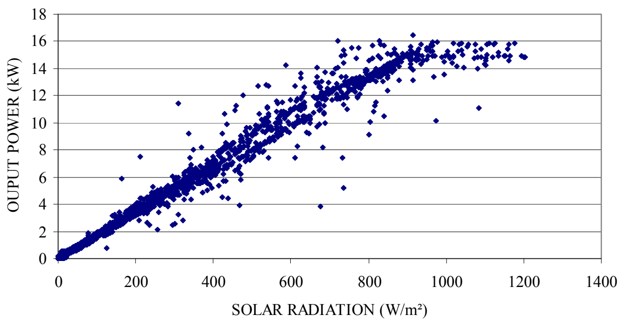

Fig. 1. Output Power vs. Solar Radiation

C. *Current harmonic profile*

The output current of the PV plant at the point of common coupling (PCC) is proportional to the power injected to the LV grid and hence, to the solar radiation. The dominant current harmonics observed through the measurement campaign are of the 3rd, 5th, 7th, 9th and 11th order. Harmonics of higher orders, basically odd ones, were also recorded but their magnitude was negligible.

During the light part of the day, which also included times of sudden variations, current harmonics were a proportion of fundamental current. On the other hand, during sunrise and sunset there was a proportionally significant injection of harmonic current (especially of the 3rd order) and the sinusoidal curve was heavily distorted.

Fig.2 depicts a scatter diagram of I_3, I_5, I_7, I_9 and I_{11} current harmonics vs. the fundamental current I_1. The 3rd order prevails in amplitude, presenting a sharp peak in small values of the fundamental current, whereas the 5th harmonic order presents a rather independent behavior regarding the fundamental current.

D. *Voltage harmonic profile*

The voltage harmonic profile of the PV plant is not affected by the solar variations. The Thd_{rms} of the voltage is between 1.6-1.25% during the operation of the PV station. It presents a rise during sunrise and sunset, when the generation is low. Nevertheless, this value drops to 0.7-1.15% after sunset.

In the measurement campaign the switches of the station opened for 20 min. The results of the 20 min recording showed that in the distribution network the 5th and 7th orders of voltage harmonics are present with average amplitude of about 2.2 V and 1.6 V correspondingly. These harmonics were also recorded when there was no solar radiation and the station did not produce any power.

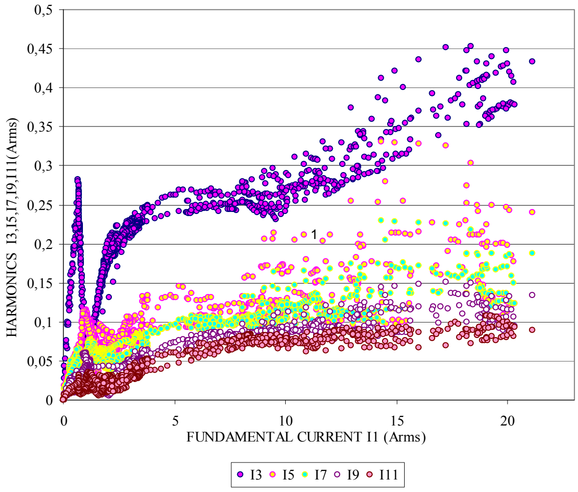

Fig. 2. Scatter diagram of Current Harmonics vs. Fundamental Current

IV. Simulation

A. *Network modeling*

In order to examine the harmonic impact of the PV plant, the background current and voltage distortion of the network should be considered [15].

The LV network where the PV plant is connected consists of an overhead line ACSR 95mm^2 with the following characteristics:

$$R' = 0.22 \text{ Ohm/km}, \quad X' = 0.36 \text{ Ohm/km}$$

The PV plant is the first installation to be connected to this line, in 100 m distance from the 250 kVA, 20/0.4 kV transformer. In the network model, the secondary voltage of the transformer was simulated as an ideal voltage source equal to 0.236 kV/ phase. Domestic loads of a total of 118 A_{rms} follow in a distance of approximately 200 m. Loads were simulated as an aggregated current source of 118 A_{rms} in the fundamental frequency.

The network impedance Z_{tot}, in the fundamental frequency, is acquired by the measurements performed by the inverters of the PV plant. The inverters are measuring Z_{tot} for reasons of anti-islanding. From this data an average value is estimated:

$$Z_{tot} = 0.69 \text{ Ohm}$$

Taking into account that Z_{tot} in 50 Hz, seen from the PCC, is 0.69 Ohm, resistance R_{1tot} and inductance X_{1tot} of the Thevenin equivalent on the right side of the PCC can be estimated. Z_{tot} is the parallel combination of Z_{1tot} and Z_{2tot}:

$$Z_{tot} = \frac{Z_{1tot} * Z_{2tot}}{Z_{1tot} + Z_{2tot}} \tag{1}$$

In the above equation Z_{1tot} is the impedance between the PCC and the transformer (Thevenin equivalent) and Z_{2tot} is the impedance between the PCC and the loads (including the impedance of the loads and the line), which is already known.

From (1) Z_{1tot} is calculated and is equal to 1.0398 Ohm. Assuming that due to the transformer, the ohm resistance $R_{1tot} = 0.2X_{1tot}$ leads to:

$$R_{1tot} = 0.202 \text{ Ohm and } L_{1tot} = 3.2149 \text{ mH}$$

Finally, the presence of 5th and 7th order of voltage harmonics when the PV plant did not produce power is due to domestic loads connected to the LV network. These loads were simulated with current sources [16], [17] in the fundamental, 5th and 7th order. Fig. 3 presents the LV network as simulated in PSIM© [18]. The amplitude and the phase angle of the current sources in 250 Hz and 350 Hz, as well as the phase angles of the current source in the fundamental frequency and the voltage source were determined after a series of simulations, as seen in Table I, so as to give the same voltages at the PCC as the ones taken from the measurements when the switches of the PV plant opened for 20 min. The comparison of the simulation results are shown in Table II. It should be mentioned that results taken from PSIM are imported in the Harmoniques [19], so that the amplitude and the angle shifts of voltages can be verified to be the same with the ones measured.

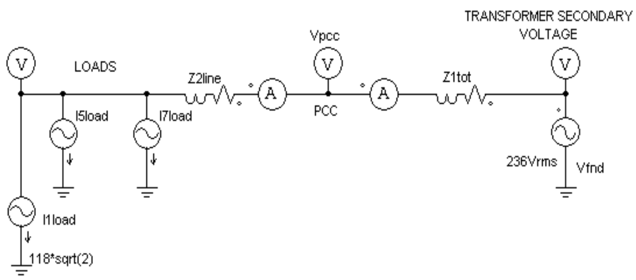

Fig. 3. Network model

TABLE I
CURRENT SOURCES OF LOADS AND VOLTAGE SOURCE OF TRANSFORMER

Harmonic Order	Current (A_{rms})	Voltage (V_{rms})
1	118 < 25°	236 < 29°
5	0.51 < 259°	-
7	0.3 < 140°	-

TABLE II
COMPARISON OF THE SIMULATION RESULTS (WITHOUT PV)

Harmonic Order	Voltage at PCC V_{rms} (PSIM- Harmonique)	Voltage at PCC V_{rms} (Measurements)
1	235.201 < -0.94°	236.063 < 0°
5	2.574 < 166.46°	2.587 < 165.64 °
7	2.133 < 48.12°	2.168 < 44.35°

B. *PV plant model*

The PV station under study consists of 3 Sunny Boy 5000TL multi-string inverters. Each inverter is connected to a string of 18 panels and a string of 19 panels. In the simulated model the inversion of the dc voltage produced by each string will be modeled separately.

The panels are considered to work at their maximum power point, which in practice is close to their nominal operation. According to the Sharp NU-S0E3E panel's specifications, the point of operation is $(V_0, I_0) = (23.7\text{V}, 7.6\text{A})$ so the series of 18 panels produces $V_{0(18)} = 23.7 \times 18 = 426.6\text{V}$ and the series of 19 panels produces $V_{0(19)} = 23.7 \times 19 = 450.3\text{V}$, which are represented by dc voltage sources.

The dc voltage generated by every PV string is converted into ac by a converter. Controls switches are used for the simulation of the converter. These switches may close and open with control signals which are applied in the control terminal of the element. In the converter modeling, Metal Oxide Semiconductor Field Effect Transistors MOSFETs are used and implemented with a conducting resistance of $R_{DS\,(ON)}$ = 44 mΩ.

Pulse Width Modulation (PWM) is used for the inversion. In this case the inverters' dc input voltage has a constant width. The inverter must control the amplitude and the frequency of the ac output voltage. This is achieved with PWM modulation of the converter's switches.

The dc voltage produced by the string of 18 panels is converted with a complete bridge of MOSFETs. One part of the bridge is controlled with the comparison of the $V_{control}$ with V_{tri}, whereas the other part is controlled with the comparison of the - $V_{control}$ with V_{tri} (Fig. 4.). The converter of 19 panels is simulated respectively.

For the voltage sources $V_{control}$ and V_{tri} of the PWM modulation in both converters, the following assumptions are made:

1) The chosen frequency of the triangular waveform is f_s = 5 kHz.
2) The amplitude of the triangular waveform is chosen to be 2 V, so the amplitude of the control signal $V_{control}$ is equal with the width modulation parameter m_a.
3) For having the preferable output voltage, the amplitude of $V_{control}$ is increased in a value more than 1 (1.2 V for the series of 18 panels and 1.1 V for the series of 19 panels).
4) For the elimination of high frequency harmonics, a low pass filter LC is placed in the output of the converter. Simulation results without the filter showed that harmonics are present for a value more than 10 kHz. So the cut off frequency of the filter is chosen in the 1/10th, i.e. f_c = 1000Hz.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \longrightarrow LC = 25 \times 10^{-9}\ [\sec^2]$$

An inductor L = 1000 mH and a capacitor C = 0.25 μF are chosen. In the PV system model one filter is placed in the output of the series of the 18 panels and one same filter is placed in the series of the 19 panels. The PV model is then connected to the PCC of the network model.

Results of voltage harmonics at the PCC are compared to the values acquired by the field measurements in Table III. It should be noticed that results in Harmoniques showed that the PV system has a power factor equal to 0.9952 with the vector of the injected current leading the vector of the V_{PCC}.

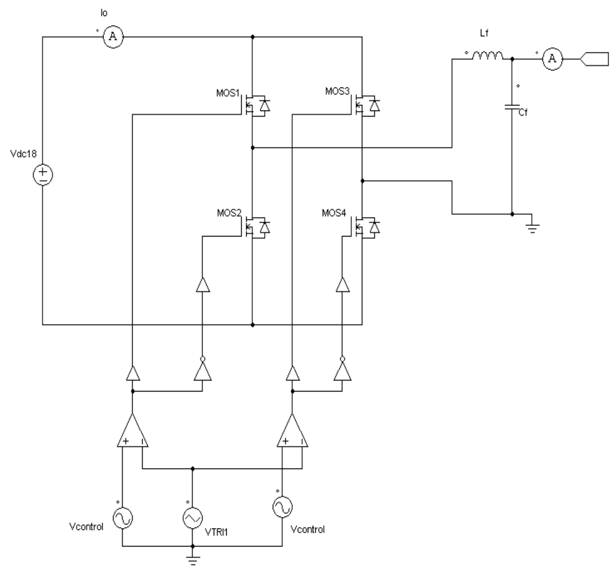

Fig. 4. 18 string inverter model

TABLE III
COMPARISON OF THE SIMULATION RESULTS (WITH PV)

Harmonic Order	Voltage at PCC V_{rms} (PSIM)	Voltage at PCC V_{rms} (Measurements)
1	236.34	239.598
3	0.871	0.450
5	2.567	3.014
7	2.167	2.088

C. Simulation's results

Having defined the models of the network and the PV, the harmonics injected in the network by the PV plant are examined. Results related to the measured PV installation, are shown in Tables IV and V.

TABLE IV
SIMULATION RESULTS OF HARMONIC CURRENTS

Results of Harmonic Currents (A_{rms})			
Harmonic Order	I_{PV}	I_{TR}	I_{LOAD}
1	16.758	101.99	117.98
3	0.313	0.358	0
5	0.111	0.562	0.564
7	0.080	0.266	0.258

TABLE V
SIMULATION RESULTS OF HARMONIC VOLTAGES

Results of Harmonic Voltages (V_{rms})			
Harmonic Order	V_{PCC}	V_{TR}	V_{LOAD}
1	236.34	235.95	234.85
3	0.871	0	0.866
5	2.567	0	2.761
7	2.167	0	2.317
Thd_{rms} (%)	1.47	0	1.58

D. Scenarios of penetration

Different scenarios of penetration level of PV plants in the specific network are considered. The test cases examined assume that the PV plants connected to the network consist of inverters with identical specifications. Thus the injected harmonic components have the same amplitudes and phases. This assumption results in the amplification of the harmonic currents generated from similar PV plants connected in parallel. Yet the actual harmonic amplitudes could be smaller than expected due to the harmonic cancellation or attenuation.

The first scenario examined assumes the connection of a second PV plant (PV#2) similar to the one modeled (PV#1) at the end of the network. Scenarios continue considering the connection of several PV plants in parallel with PV#1 at PCC_1 and PV#2 at PCC_2. Table VI shows some indicative results of the simulations. The penetration level is defined as the ratio of the total capacity of the PV plants to the nominal capacity of the transformer (250 kVA). V_{PCCn} and Total Harmonic Distortion (Thd_{rms}) are for both PCCs.

TABLE VI
SIMULATION RESULTS OF PENETRATION SCENARIOS

Penetration Level (%)	V_{PCC1} (Vrms)	V_{PCC2} (Vrms)	Thd_{rms} (%) of PCC_1	Thd_{rms} (%) of PCC_2
16	238.06	237.07	1.64	1.74
24	240.14	238.76	1.84	1.94
32	242.41	240.68	2.22	2.32
40	244.84	243.47	2.29	2.39
48	247.45	244.19	4.79	4.95
56	250.07	246.50	6.42	6.60
64	252.49	248.63	7.20	7.40
72	255.40	251.27	8.87	9.11

Simulation results showed a violation of the harmonic limits when the penetration level reached 72% of the rated capacity of the transformer. The Thd_{rms} exceeded the limit of 8% posed by the standards [1], [2] in both PCCs. The violation was more intense in the end of the network (PCC_2) where the Thd_{rms} reached the value of 9.11%. Furthermore, overvoltage was also noticed at the PCC_1. The voltage in this case overreached 253 V which is the U_n +10% limit [1]. Beyond that point of penetration, the connection of more PV plants presents harmonic and voltage problems.

For all the cases examined, the Total Demand Distortion (TDD) has been estimated with the Local EPS maximum load current integrated demand, according to [2]. The current harmonic limit, i.e. TDD < 5% was not violated.

E. Setting of the parameters of the PV inverters

In this chapter, the parameters of the PV inverters are adjusted and the injected current harmonics, as well as the voltage at the PCC are investigated. The scope is to examine the influence of the inverter's parameters on the harmonic behavior of the PV plant.

All the scenarios here assume that there is one PV plant connected to the PCC_1 of the previous network. Simulations were performed in the 18 string inverter, in the 19 string inverter and in both 18 and 19 string inverters.

In the first test case (#1), the frequency of the triangular voltage source V_{tri}, initially settled in 5 kHz, is adjusted for various nominal values, i.e. $f < 6$kHz or $f > 20$kHz. Implementing smaller frequencies, e.g. 3, 4 kHz, to the V_{tri} of the 18 string inverter showed insignificant alterations of the V_n and I_n, both amplitude and phase, with Thd_{rms} of voltage and current having rather flat values of approximately 1.52% and 1.97% correspondingly. The same conclusions were drawn when small frequencies were implemented in both 18 and 19 string inverters. On the other hand, when setting the frequency of the 18 string inverter in higher values, e.g. 20, 30 kHz, the Thd_{rms} of the voltage decreased to values of 1.49%. Thd_{rms} of the current remained in a range of 1.98%, but increased when the 19 string inverter had the same parameters' adjustment. Table VII presents a sample of the results of test case #1.

TABLE VII
SIMULATION RESULTS OF TEST CASE #1

Frequency (kHz) of V_{tri} of 18 string inverter	V_3 (V)	I_3 (A)	V_5 (V)
3	0.968<156.64	0.313<73.99	2.65<153.97
4	0.967<157.26	0.312<73.80	2.65<154.32
30	0.947<160.71	0.313<73.85	2.63<155.49
Frequency (kHz) of V_{tri} of 18 and 19 string inverter	V_3 (V)	I_3 (A)	V_5 (V)
3	1.02<152.46	0.312<73.93	2.69<152.22
4	0.992<154.75	0.312<73.23	2.66<153.29
40	0.960<161.11	0.318<74.22	2.60<155.38

The second test case (#2) examines the behavior of the harmonic components when the amplitude of the V_{tri} is decreased. In the beginning, simulations were performed by decreasing the V_{tri} of the 18 string inverter from 2 V to 0.5 V by steps of 0.1 V. The alterations of the V_{PCC}, in the harmonic orders examined, are insignificant both for the amplitude and the phase. The only remarkable case was the phase of the V_3, as seen in Table VIII. On the other hand, alterations of the I_n were observed and Thd_{rms} of the output current was increased from 1.38% to 3.52%. The same behavior was marked when corresponding settings were performed in the V_{tri} of the 19 string inverter. Finally, simulations were performed by changing the amplitude of the V_{tri} of both 18 and 19 string inverters. The alterations here for the V_n and the I_n are more intense. Table VIII and Table IX summarize the results.

TABLE VIII
V_N OF TEST CASE #2

V_{tri} (V) of 18 string inverter	V_3 (V)	V_5 (V)	V_7 (V)
1.8	1.276<160.30	2.576<156.43	2.022<48.06
0.9	0.513<159.17	2.788<150.94	2.137<44.46
0.6	0.879<-14.49	3.345<138.18	1.880<48.55
V_{tri} (V) of 18 and 19 string inverter	V_3 (V)	V_5 (V)	V_7 (V)
1.8	1.773<158.56	2.659<155.97	1.920<49.06
0.9	0.811<-11.19	3.507<137.36	1.887<49.12
0.6	1.748<-14.44	3.899<131.51	1.623<53.71

TABLE IX
I_N OF TEST CASE #2

V_{tri} (V) of 18 string inverter	I_3 (A)	I_5 (A)	Thd_{rms} (%)
1.8	0.450<73.65	0.100<-16.48	2.72
0.9	0.191<70.59	0.163<-6.99	1.51
0.6	0.259<-101.24	0.332<-1.17	2.61
V_{tri} (V) of 18 and 19 string inverter	I_3 (A)	I_5 (A)	Thd_{rms} (%)
1.8	0.609<72.66	0.107<-11.93	3.59
0.9	0.055<66.54	0.219<-5.11	1.37
0.6	0.921<-106.14	0.529<-0.36	6.93

Finally the last test case (#3) assumes different amplitudes of the sinusoidal voltage source $V_{control}$ of the PWM. The $V_{control}$ was decreased from 1.2 V to 0.2 V by steps of 0.1 V. When the setting took place in the 18 and 19 string inverter separately results were rather the same, with the fundamental voltage dropping and the voltage harmonics insignificantly affected. On the contrary the harmonic currents were affected and the Thd_{rms} was decreased. Relative conclusions were drawn when the adjustment was performed in both 18 and 19 string inverters. Table X presents a sample of the test case's results.

TABLE X
SIMULATION RESULTS OF TEST CASE #3

$V_{control}$ (V) of 18 string inverter	I_3 (A)	I_5 (A)	Thd_{rms} (%)
1	0.094<67.05	0.05<-41.54	0.66
0.7	0.092<77.34	0.045<-48.19	0.72
0.5	0.089<85.25	0.045<-51.8	0.75
$V_{control}$ (V) of 18-$V_{control}$ (V) of 19 string inverter	I_3 (A)	I_5 (A)	Thd_{rms} (%)
1-0.9	0	0.044<-102.69	0.30
0.7-0.6	0	0.041<-125.55	0.50
0.5-0.4	0.051<177.89	0.048<-138.06	0.98

V. Discussion on the results

The connection of the PV plant in the distribution network causes the presence of the 3rd order of current and voltage harmonic. I_3 generated by the PV plant flows to the transformer, whereas a voltage in the 3rd order appears at the side of the loads. The operation of the PV plant close to its rated power causes no violation in the harmonic limits posed by the standards [1], [2].

In the scenarios of penetration, when the level reached approximately the 72% of the total capacity of the transformer, the voltage harmonics exceeded the allowable limits, whereas the current harmonics remained within the range. Overvoltage at the PCC_1 was also observed.

Due to the above results the issue of the influence of the inverters' parameters on the harmonic behavior of the PV plant aroused. So the question was if PV inverters with appropriate settings can cause elimination of the harmonic components.

Results showed that the modification of the frequency of the V_{tri}, even in values of 20 kHz, does not affect the output voltage and in consequence the injected harmonics. In the scenarios where the amplitude of the V_{tri} and the $V_{control}$ is adjusted, alterations of the phases of V_3 and especially of all the current harmonics were observed.

VI. Conclusions

This paper reviews the results from field measurements in a 20 kWp PV plant connected in the distribution network. The harmonic behavior regarding the solar radiation and the output current is being examined. A model of the PV plant was developed in the PSIM© and Harmoniques© software packages and the impact of the PV plant in the distortion of the current and voltage waveform is then been investigated. Penetration scenarios were then examined by connecting in parallel similar PV plants at two points of the LV network. Simulation results showed violation in the voltage harmonic limits posed by international standards and overvoltage. Finally, the behavior of the harmonic components, including the amplitude and the phase, is examined for various settings of the PV inverters' parameters. A further study will include a combination of the above settings in order to attenuate the harmonic impact of PV plants connected in parallel.

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VIII. Biographies

Ioulia T. Papaioannou (b. 1980) received the Dipl.-Eng. Degree from the Department of Electrical and Computer Engineering at the Aristotle University of Thessaloniki, in 2004.

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Charis S. Demoulias (b. 1961) received his Dipl. Degree and the Ph.D degree from the Department of Electrical Engineering at the Aristotle University of Thessaloniki in 1984 and 1991 respectively.

He worked as a consultant in the areas of industrial electrical installations, electrical energy saving, and renewable energy sources. He is currently lecturer with the Electrical Machines Laboratory, Department of Electrical and Computer Engineering in the Aristotle University of Thessaloniki.

His research interests are in the fields of power electronics, harmonics, electric motion systems and renewable energy sources.

Dimitris P. Labridis (b. 1958) received the Dipl.-Eng. Degree and the Ph.D. degree from the Department of Electrical Engineering at the Aristotle University of Thessaloniki, in 1981 and 1989 respectively.

Since 1986 he has been with the Electrical Engineering Department, Aristotle University of Thessaloniki, Greece, where he is currently an Associate Professor.

His research interests are power system analysis with special emphasis on the simulation of transmission and distribution systems.

Petros S. Dokopoulos (b. 1939) received the Dipl. Eng. Degree from the Technical University of Athens in 1962 and the Ph.D. degree from the University of Brunswick, Germany, in 1967.

Since 1978 he has been full professor at the Department of Electrical Engineering at the Aristotle University of Thessaloniki, Greece. He is currently Professor Emeritus with the same institution.
His scientific fields of interest are dielectrics, power switches, generators, power cables, alternative energy sources, transmission, distribution and fusion.