ANALYSIS OF GRID-CONNECTED PHOTOVOLTAIC SYSTEM INTEGRATON ON LOW-VOLTAGE DISTRIBUTION NETWORK

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Abstract - The introduction of new local sources on the distribution network will impact the quality of power in different ways. The low-voltage customers are strongly affected by the level of power quality, especially by harmonic distortions. In present paper, the impact on the power quality of a low-voltage utility network with an integrated PV system has been assessed at the point of common coupling of the PV system. In this order, the most representative power quality indices concerning the harmonic distortion have been monitored and compared with the limits set by the corresponding standards.

Keywords: photovoltaic system, power quality indices, annual energy production.

1. INTRODUCTION

Around the whole world, electric energy from photovoltaic (PV) systems is considered as an important generation alternative in the electric power supply. In this order, in the last years, the integration of photovoltaic systems has registered a growing interest compared with other renewable energy sources.

Most of applications with PV systems are on-grid or grid connected systems. The grid-connected applications are used to provide energy in utility network. The tie-grid inverter is one the most important component of grid-connected PV systems. Its role is to convert direct current (DC) to alternating current (AC) and also to synchronize the output power with the system frequency.

For tie-grid inverters, the output voltage is synchronised with the grid voltage whereas the current should be a sinusoidal wave. Unfortunately, all power electronic components used in different types of tie-grid inverters can affect the current waveform. Inverters can strongly increase the currents and also the voltages harmonic disturbances by injecting harmonic currents directly into the grid. An important characteristic of inverters is the harmonic distortion of output power.

The power quality standards require that the tie-grid inverters used in PV systems should not affect the quality of the voltage at the point of common coupling and that the current injected into the grid should be of high quality. Harmonic distortion in the low-voltage utility network can cause problems if the sum of the harmonic distortions increases above certain limits. A grid-connected PV inverter whose harmonic current injected into the grid does not exceed these limits can be connected anywhere without any difficulty and special requirements.

Considering these issues, the main objective of this paper is to analyse the impact (positive or negative) on the power quality of a low-voltage utility network with an integrated PV system operated under real conditions. The study conducted in this paper is organized as follows. Section II presents a brief review of main representative standards concerning harmonics on low-voltage utility networks. The photovoltaic system under analysis belongs of LACARP Laboratory and is described in Section III. In order to evaluate the effects of the PV system integration on low-voltage utility network, in Section IV some measurements have been performed in order to evaluate the harmonic contents of the output power and results have been compared with the limits sets in the standards. Finally, the main conclusions of this paper are given in section V.

2. REPRESENTATIVE INDICES AND STANDARDS ON HARMONICS

Different power quality indices are defined in the literature in order to measure the level of harmonic distortion. The most common index used to indicate the harmonic content of a distorted waveform is the Total Harmonic Distortion (THD). It is a measure of the effective value of the harmonic components of a distorted waveform, which is defined as the RMS of the harmonics expressed in percentage of the fundamental component:

$$THD_Y = \frac{1}{Y_1}\sqrt{\sum_{k=2} Y_k^2} \qquad (1)$$

where Y_k is the RMS of absolute harmonic component, and k is the order of the harmonic.

Depending on the types of analysed waveform, two THD are defined: the Total Voltage Harmonic Distortion (THD_V) and Total Current Harmonic Distortion (THD_I).

Concerning the standards, a literature survey [1,2,3] indicates that whole literature related to power quality refers to three representative standards issued by three different organizations, these standards being IEEE 519, IEC 61000 and EN 50160. In the following subsections, these three standards are briefly presented in accordance with the main subject of paper, focused only on disturbance at low-voltage level.

a) Standard IEEE 519

Standard IEEE 519-1992 specifies limits of total harmonic distortion and also the level of each individual harmonic component. Recommended limits are provided for both voltage and current harmonic distortions.

According to IEEE 519, harmonic voltage distortion on power systems limited the total harmonic distortion to 5% and each individual harmonic distortion to 3%. Furthermore, the standard establishes the limits of harmonic current distortion at the point of common coupling (PCC). The limits dependent on the ration of short-circuit current to maximum load current at the PCC. Table 1 indicate the harmonic current limits and THD_I at the point of common coupling at voltages below 69 kV. For voltage from 69 to 161 kV, the limits are 50% of the limits above. A case-by-case evaluation is required for PCCs of 161 kV and above. As can be seen, Table 1 summarised only the odd harmonics, even harmonics being limited to 25 % of the above odd harmonic limits.

Table 1. Levels for individual harmonic current in the low-voltage network (IEEE 519-1992)

	Harmonic order (only odd harmonics)					
I_k/I_L	k<11	11≤k<17	17≤k<23	23≤k<35	35≤k	THD_I
< 20	4	2	1.5	0.6	0.3	5
20-50	7	3.5	2.5	1	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
> 1000	15	7	6	2.5	1.4	20

For stronger low-voltage networks, with typically larger short-circuit ratio values, are allowed higher percentages of harmonic current than for the weaker networks with smaller short-circuit ratio values. As can be seen, the least restrictive limits of total current harmonic distortion is 20%, whilst for the individual harmonic current distortion at PCC is 15 %. These values are expressed as the percentage of the fundamental current.

b) Standard IEC 61000

The IEC 61000 series contains six parts, each of them including others standards and technical reports. The most commonly used references for power quality for low-voltage utility network are IEC 61000-2-2, IEC 61000-3-2 and 61000-3-4, respectively.

Table 2. Compatibility levels for individual harmonic voltage in the low-voltage network (IEC 61000-2-2)

Odd Harmonics				Even harmonics	
Not Triplen Harmonics		Triplen Harmonics			
Order k	Harmonic voltage (%)	Order k	Harmonic voltage (%)	Order k	Harmonic voltage (%)
5	6	3	5.0	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0,5
13	3	21	0.2	8	0.5
17	2	>21	0.2	10	0.2
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	0.2+1.3·25/k				

Standards IEC 61000-3-2 and 61000-3-4 are in accordance with IEC 61000-2-2 that indicates the compatibility levels for individual harmonic voltages in the low-voltage network, these levels being tabulated in Table 2. The THD_V of the supply voltage including all harmonics up to the 40^{th} order have to be less than 8%.

Concerning harmonic current distortion in low-voltage utility networks, both IEC 61000-3-2 and 61000-3-4 define limits for individual harmonic current for equipment drawing input current of up to and including 16 A per phase whilst the second one includes equipment with a rated current greater than 16 per phase, respectively.

Furthermore, IEC 61000-3-2 includes a classification of load into four categories and the limits of harmonic currents depend on these categories. Table 3 reports limits of harmonic currents for all four classes, for equipment drawing input current of up to and including 16 A per phase.

Table 3. Limits of harmonic current in accordance with IEC 61000-3-2

`		Max. permissible harmonic current order			
		Class A (A)	Class B (A)	Class C (% of fund.)	Class D (mW/A)
Odd order k	3	2.3	3.45	$30 \cdot P_{ower}F_{actor}$	3.4
	5	1.14	1.71	10	1.9
	7	0.77	1.155	7	1.0
	9	0.4	0.6	5	0.5
	11	0.33	0.495	3	0.35
	13	0.21	0.315	3	3.85/13
	15-39	0.15 ·15/k	0.225 ·15/n	0.15	3.85/k
Even order k	2	1.08	1.62	2	-
	4	0.43	0.645	-	-
	6	0.30	0.45	-	-
	8-40	0.23 · 8/k	0.345 ·8/n	-	-

According to IEC 61000-3-4, the maximum harmonics current limits for equipment with a rated current greater than 16 A per phase, are tabulated in Table 4.

Table 4. Limits of harmonic current in accordance with IEC 61000-3-4

Odd order k	Max. permissible harmonic current order (%)	Odd order k	Max. permissible harmonic current order (%)
3	21.6	19	1.1
5	10.7	21	0.6
7	7.2	23	0.9
9	3.8	25	0.8
11	3.1	27	0.6
13	2	29	0.7
15	0.7	31	0.7
17	1.2	33	0.6

c) Standard EN 50160

Standard EN 50160 specifies voltage characteristics in LV and MV distribution systems at the customers' terminals, under normal operating conditions. The values of individual harmonic voltages in the low-voltage utility network, for orders up to 25, are tabulated in Table 5 as percentage of the fundamental voltage. The total voltage harmonic distortion including all harmonics has to be less than 8% for 95% of the time of week.

Romania has adopted EN 50160 standard as the basis for national quality regulation on public distribution systems [3].

Table 5. Values of individual harmonic voltages in the low-voltage networks (EN 50160)

Odd harmionics				Even harmonics	
Not Triplen Harmonics		Triplen Harmonics.			
Order k	Harmonic voltage (%)	Order k	Harmonic voltage (%)	Order k	Harmonic voltage (%)
5	6	3	5,0	2	2,0
7	5	9	1,5	4	1,0
11	3,5	15	0,5	6÷24	0,5
13	3	21	0,5		
17	2				
19	1,5				
23	1,5				
25	1,5				

EN 50160 Standard limits individual harmonic voltage distortion but does not specify current harmonics requirements for power quality in the public distribution system.

3. LACARP PHOTOVOLTAIC SYSTEM

The photovoltaic system under analysis is located in Iasi, Romania, belonging of Faculty of Electrical Engineering, Technical University of Iasi, as part of LACARP Laboratory, a modern research laboratory developed as result of a research project of Power Engineering Department (see Fig. 1).

Fig. 1. View of LACARP PV system

The PV system is developed in order to operate as a grid connected as well as a stand-alone PV system, depending on research objectives. In this paper are evaluated the power quality indices of PV system as a grid-connected system.

The PV system has an installed capacity of 3 kW_p, being consisted of 12 polycrystalline silicon modules, SM-250PC8 manufactured by S-Energy. The PV modules are arranged in one string being connected to a Sunny Boy 3000 TL single-phase inverter, the inverter being tied by national grid to 0.4 kV (Fig. 2). The three-line electrical diagram of PV system is shown in Fig. 3. The inverter is equipped with an OptiTrack Global Peak management system with allows to find and use the optimal operating point of partially shaded PV modules.

Fig. 2. Sunny Boy and Sunny Island inverters

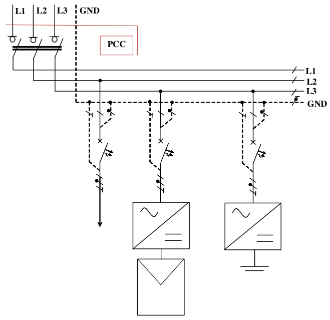

Fig. 3. Three-line diagram of LACARP PV system

Concerning the distortion limits, the technical data of inverter indicate a total harmonic distortion of the output current below 4%, for a total harmonic distortion of the output voltage up to 2% and an output power higher than 50% of the rated power.

The PV system is in operation since December 2013 and it has been continuously monitored, complete operation data for the years 2014 and 2015 being summarised in Fig. 4. The output power database has been recorded using a Sunny WebBox module, which ensures an interface between PV system and operator, providing information about the hourly, daily, monthly and annual energy production.

Fig. 4. Monthly energy production of PV system

Furthermore, the PV performance ratio has been carried out, its value being distributed within the range of 8.5–69.2%, and the annual value of performance ratio have been found around 50%. This lower value of performance ratio is due to permanent shading of the PV system by surrounding buildings. The 2014 annual energy production was 3012 kWh, whereas in 2015 was around 3431 kWh.

4. MEASEUREMENTS AND ANALYSES

In order to evaluate the harmonic content of the grid voltage and current at the output of the PV inverter, some measurements have been performed under real operating conditions. The power quality indices have been measured using a three phase power quality analyser - Fluke 434, whereas the output power changed by the PV system with low-voltage grid have been monitored using a three phase power logger - Fluke 1735.

The power analyser and power logger (Fig. 5) have been each connected to the output of the inverter trough three current clamps used to measure the current of each phase, as well as five voltage probes connected to each phase, on neutral and ground in order to measure the voltage.

Fig. 5. Fluke instruments used for measurements

Fig. 6 shows the current and voltage waveforms at the PCC of inverter with power grid. The single-phase inverter is interconnected with the power grid through L3 phase, in this order the analyses of the distortion are focused on this phase. As can be seen in this case, with the PV inverter injecting power in the grid to around 20% of its rated power, the voltage waveform is slowly affected by distortions, whereas the current waveform is strongly affected by harmonics.

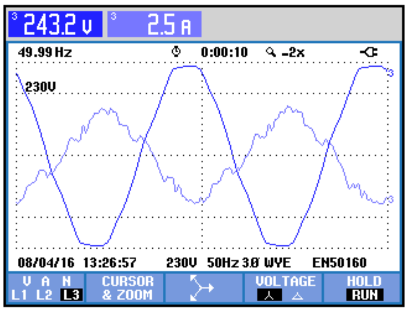

Fig. 6. The current and voltage waveforms at the PCC of inverter with power grid

The same comments can be drawn from figures 7 and 8, where are indicated the voltage and current harmonics spectrums. First screen from fig. 7 shows the voltage spectrum measured by Fluke 434 and second screen shows the RMS of each voltage harmonic component.

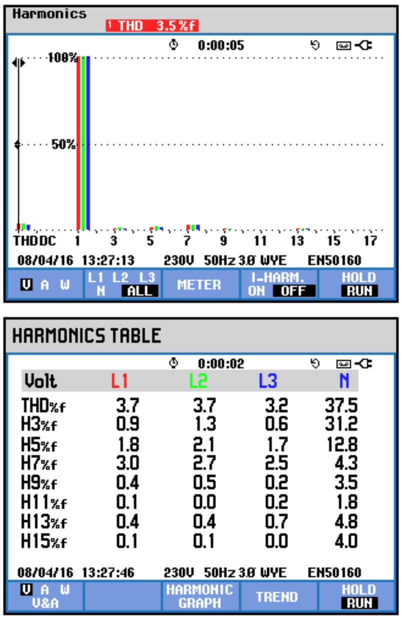

Fig. 7. Voltage harmonics spectrum at PCC

The most restrictive limits for THD_V and also for the individual voltage harmonics are in IEEE 519, where the standard limits value of THD_V to 5% and values of individual voltage harmonics to 3%. It can be seen from second screen from fig. 7 that the total voltage harmonic distortion index and also the individual harmonic components do not exceed the limits set by this standard.

Fig. 8 shows the current spectrum monitored by the Fluke 434. The harmonic spectrum, depicted in first screen, contains both odd and even harmonics for current, whilst, in second screen, only odd harmonics are considered.

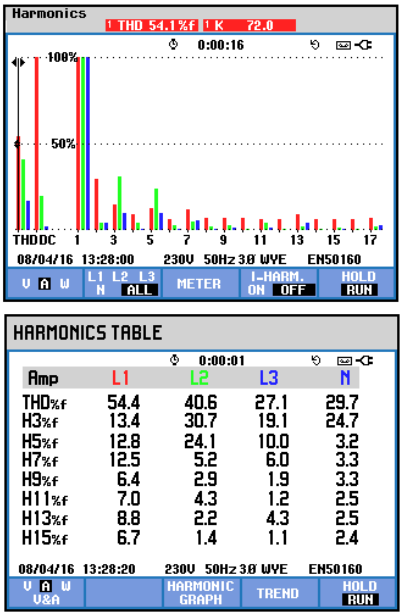

Fig. 8. Current harmonics spectrum at PCC

As can be seen, a high harmonic content on current is observed, the total harmonic distortion index THD_I has higher values than the maximum limits set in the IEEE 519 standard. Moreover, the third harmonic current is considerably higher than it should be, its value 27.1% exceeding the limits from standard. Instead, under these output conditions, with an injected current around 2.5 A, the third harmonic current is 0.48 A, thus, in this case, the limit values for harmonic current stated by EN 61000-3-2 (class A) are not exceeded. The PV inverter is equipment that can not belong to classes B, C and D, being classified into class A.

With regards to the evolution of harmonic content on the voltage and current waveforms, few days monitoring of THD_V and THD_I has been performed. It was analysed the evolution in time of voltage and current harmonics distortion. For this, it has been continuously monitored the harmonic contents for few days, between April 5th and April 8th. The monitored data acquired by the instruments Fluke 434 and Fluke 1735 have been processed for same time interval of 100 hours and with 5 minutes averaging interval.

Therefore, fig. 9 shows the evolution of total voltage harmonic distortion and fig. 10 shows the evolution of individual 3rd, 5th and 7th harmonics for L3 phase, with respect to the power exchanged by the PV system with the low-voltage grid at the point of common coupling.

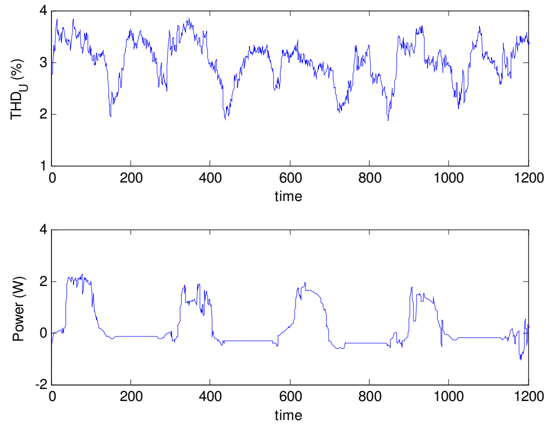

Fig. 9. Total voltage harmonic distortion

The voltage distortion is due to the current demanded by nonlinear loads connected downstream of the PCC (i.e. non-linear inductors from the ballasts of fluorescent lights) and also to the current injected by the PV system, both currents flowing through the impedances of the grid, affecting then the voltage waveform.

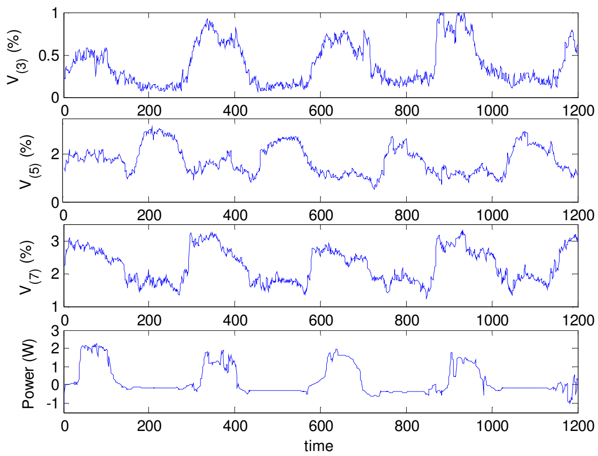

Fig. 10. Individual harmonic voltage distortion

As can be seen from previous figures, the evolution of total voltage harmonic distortion and their individual harmonics content does not exceed the limits set by the IEEE 519 standard, so in terms of voltage distortion, the effect of PV system operation is negligible. These conclusions concerning the voltage distortion are in concordance with those found in literature [4,5].

With regards to the evolution of harmonic content of the current, the monitored data have been analysed. Fig. 11 shows the evolution in time of total current harmonic distortion THD_I, their behaviour denotes a large range of values' variation.

The experimental results show that the total current harmonic distortion at the output of the inverter depends strongly on the inverter output power. Maximum values of total current harmonic distortion have been measured during night and at low active power operation, whereas the minimum values have been observed when the PV inverters operated close to their nominal power. Similar conclusions are founded by different authors in their works [6,7].

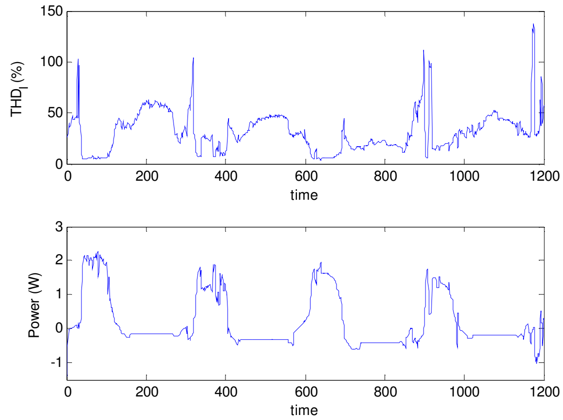

Fig. 11. Total current harmonic distortion

Concerning the individual harmonic current evolution, the low order (3^{rd}, 5^{th} and 7^{th}) current harmonics for L3 phase have been individually investigated, their evolutions, expressed as the percentage of the fundamental current, being depicted in fig. 12.

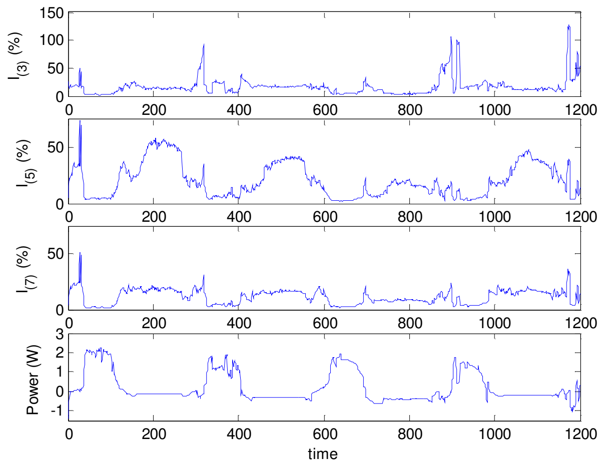

Fig. 12. Individual harmonic current distortion

As can be seen in fig. 12, individual harmonic current evolution has a similar behaviour for all three odd order harmonics. The behaviour is directly related to the output power injected by PV inverter into grid, high individual harmonics currents being observed during the night and at lower levels of generated power. This can be due to the fact that the magnitude of fundamental component of current during the night and at morning and evening hours has lower values, being directly related on amount of solar radiation falling on PV panels. The higher order current harmonics, over the 9^{th} order, have negligible values, in this order these harmonics have not been considered. As can be seen from previous figures, during the daily hours, especially in sunny days, the THD_I and also the individual harmonic current have lower values, whilst in the cloudy days, the harmonic contents have a large variation. For instance, in the first day of measurements, the THD_I have a lower value around to 5.7%, for second and fourth days have a variation between 6.7% and 95%, whilst, in third day, THD_I ranges between 5.3% and 44%.

5. CONCLUSION

This paper approaches a problem of actuality, concerning the effect on power quality of low-voltage utility networks with integrated PV systems.

The paper presents, based on a literature survey concerning the harmonic distortion in low-voltage utility networks, the limits stated by the three main standards IEEE 519, IEC 61000 and EN 50160.

In order to evaluate the power quality of low-voltage distribution system with integrated PV system, the main indices with regard to harmonic contents have been monitored, for different reference periods, at the point of common coupling of the photovoltaic system.

Regarding the total voltage harmonic distortion, it can be noted that the inverter operated without exceeding the regulation limits. Regarding the harmonic content of the inverter current depends strongly on the inverter output power, the THD_I value decreases with the increase of output active power of the PV inverter.

In further papers, based on long time acquired data, the research will be focused on a statistical analysis of harmonic contents with respect to output power of PV system.

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