

ELECTRICAL SIGNATURE OF GRID CONNECTED PHOTOVOLTAIC SOURCE: A PRELIMINARY STUDY

Daniele Gallo¹, Carmine Landi¹, Mario Luiso¹

¹ Department of Information Engineering, Second University of Naples
Via Roma 29, 81031 Aversa (CE), Italy
Tel: +39-0815010375, Fax: +39-0815037042
Email: {daniele.gallo, carmine.landi, mario.luiso}@unina2.it

Abstract: Since the penetration of photovoltaic (PV) systems in the electrical network is increasing, the need to register and model the contribution of these systems, in terms of disturbances and power availability, is becoming a crucial key for optimal management of grid. On the other hand, electrical signature of sources and loads is the unique generation/consumption pattern intrinsic to each individual electrical appliance/piece of equipment. So, this paper, starting from the analysis of the disturbance impact of a 20 kW grid connected PV system, performs a preliminary study on building a method to better understand and explore the nature of electricity generation patterns of PV plants. Through this knowledge, it is possible to explore and develop innovative applications to achieve better utilization of resources and develop more intelligent ways of operation in new smart grids.

Key words: voltage measurement, current measurement, power quality measurement, photovoltaic plant.

1. INTRODUCTION

The use of PV systems is becoming wide in many countries as a result of active government policies for renewable energy sources. This trend arouses much concern on the current and voltage distortion caused by the power electronics used by these systems. Some issues that arise from the use of PV generation are as follows:

1) The disturbance 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 disturbance limits, posed by the standards EN 50160 [1] and IEEE 1547 [2], being exceeded.

This paper starts from the analysis of the results of a measurement campaign performed several days of April 2011 in a 20 kW PV plant in Avellino (in Southern Italy). This analysis aims to capture the electrical behavior of the PV plant ([3]-[5]), in order to perform a preliminary study on building a method to better understand and explore the nature of electricity generation patterns of PV plants. Through this knowledge, it is possible to explore and develop innovative applications to achieve better utilization of resources and develop more intelligent ways of operation

in new smart grids. The paper is organized as follows: in section 2 there is the description of the site and the utilized instrumentation. In section 3 there are the first experimental results and preliminary considerations on how to build a model of PV plants in order to accurately plan operation of the smart grids.

2. DESCRIPTION OF THE MEASUREMENT CAMPAIGN

2.1 Description of the site

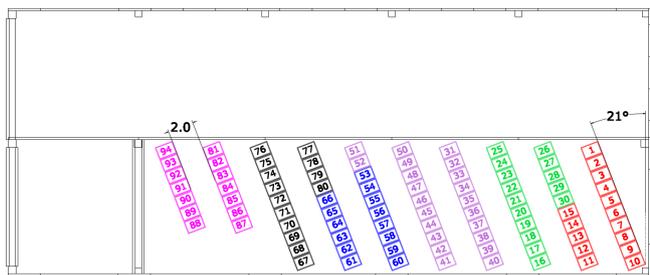
The PV station studied in this work is a system, with power equal to 19.82 kW, situated in Avellino, in the south of Italy. The station is installed on a portion of a flat roof of an industrial plant: it is a new installation operating since November 2009 and it is directly connected to the LV distribution system, without isolation transformer. It consists of six strings and two 10 kW three-phase inverters, each one having two DC inputs with separate maximum power point trackers (MPPT). For each inverter, at one input one single string is connected and at the other input the parallel of two strings is connected. The strings are made by panels having powers of 200 W, 210 W and 220 W. In Table 1 the main specifications of the PV station are summarized. In Fig. 1 a photo of the PV station is shown. In Fig.2 the positioning of the panels on the flat roof is shown.



Fig. 1. A photo of the PV station.

Table 1. Main specifications of the PV station.

Inverter	MPPT	Number of panels	Peak Power [W]	Rated Voltage [V]	Open Circuit Voltage [V]	Rated Current [A]	Short Circuit Current
Inverter 1	1	22	4400	588.94	683.1	7.47	7.97
	2	14	2940	422.5	510.72	7.06	7.55
		14	2940	422.5	510.72	7.06	7.55
Inverter 2	1	14	2940	422.5	510.72	7.06	7.55
	2	15	3300	459	553.35	7.24	7.74
			15	3300	459	553.35	7.24



LEGEND:

- String n. 1: 22 x 200Wp
- String n. 2: 14 x 210 Wp
- String n. 3: 14 x 210 Wp
- String n. 4: 14 x 210 Wp
- String n. 5: 15 x 220 Wp
- String n. 6: 15 x 220 Wp

Fig. 2. Positioning of the panels on the roof.

2.2 Instrumentation

In the measurement campaign, direct current (DC) and alternate current (AC) electrical quantities and solar irradiance have been measured. The solar irradiance has been measured through a pyranometer. It is composed by a radiometer and a pyranometric probe. The radiometer is the Delta Ohm HD 2302.0: it measures illuminance, luminance, PAR and irradiance depending on the connected probe. It communicates measurement data through RS-232 serial connection. The used probe is the LP PYRA 02 whose main characteristics are sensibility of $10 \mu\text{V}/(\text{W}/\text{m}^2)$, measurement range of $0 \div 2000 \text{ W}/\text{m}^2$ and non linearity $<|\pm 1|\%$. Regarding the electrical measurements, only the electrical quantities related to Inverter 1, indicated in Table 1, have been measured. In particular, the three DC voltages and the three DC currents of the three input strings of Inverter 1 and the three AC output voltages and the three AC output currents of the Inverter 1 have been measured. The measurement of AC and DC electrical quantities has been performed through a specifically built instrument. It is composed by a personal computer (PC), a data acquisition board (DAQ) and voltage and current transducers (VT and CT). The DAQ has 16 analog inputs, resolution of 16 bit, maximum sampling frequency of 250 kHz, input range of $\pm 10 \text{ V}$. Six VT and six CT have been used: all the voltages have been sensed through LEM CV3-1000, three DC currents through LEM CT-10 and three AC currents through

Fluke i400. The waveforms have been sampled at frequency of 10 kHz and stored in memory. The measurement software has been written in LabVIEW environment. In Fig.3 the positioning of the measuring instruments is shown.

3. A PRELIMINARY STUDY ON ELECTRICAL SIGNATURE OF THE PV PLANT

The measurement campaign has been conducted during several days between April and July 2011. In the following subsections some of the main results of the campaign are shown.

3.1 Normal operating conditions

During the normal operating conditions the time domain waveforms of the electrical quantities appear as they are shown figures from 4 to 11. In particular Fig.4 and Fig.5 show respectively inverter output voltages and currents; Fig.6 and Fig.7 show respectively current and voltage of String 1, Fig.8 and Fig.9 show respectively current and voltage of String 2, Fig.10 and Fig.11 show respectively current and voltage of String 3. AC voltages appear to be quite sinusoidal, while AC currents appear to be quite distorted. Regarding DC voltages and currents, they have a superimposed ripple over the DC value: it is due to the MPPT, which imposes continuous little variations to voltage (and thus to the current) in order to research the maximum power point. Such a ripple has frequency of 5 Hz for String 2 and String 3 (both connected to MPPT2), while for String 1 it has two tones having frequencies of 1 Hz and 5 Hz.

3.2 Efficiency

An important parameter of an energy conversion system is its efficiency. In the case of a grid connected PV source, the energy passes through two conversions: from solar irradiance to DC electrical energy and from DC to AC electrical energy. The efficiency of the first conversion is here denoted as η_1 , while efficiency of second conversion is denoted as η_2 . The total efficiency η is the product of η_1 and η_2 . They are defined as follows:

$$\eta_1 = \frac{P_{DC}}{I} \quad (1)$$

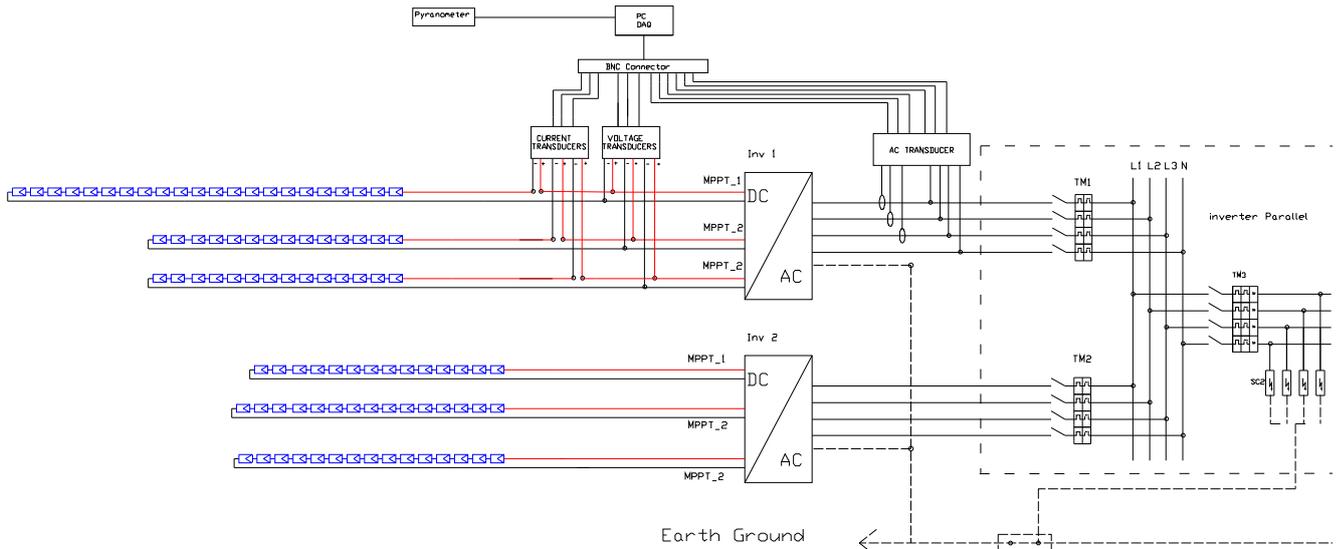


Fig. 3. Positioning of the measuring instruments

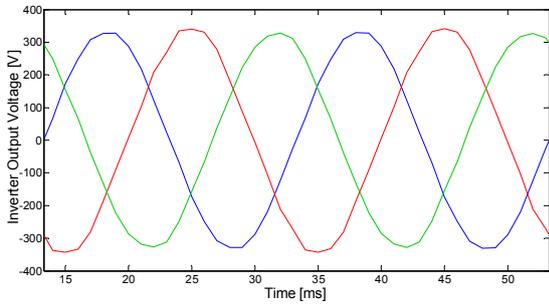


Fig. 4. Inverter output voltages

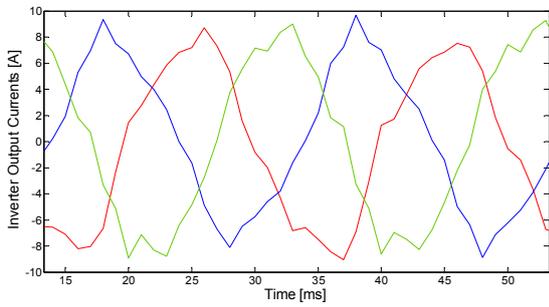


Fig. 5. Inverter output currents

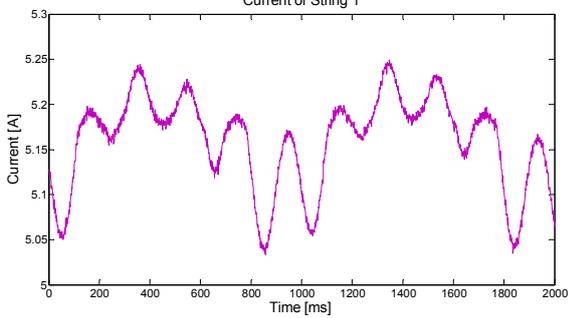


Fig. 6. Current of string 1

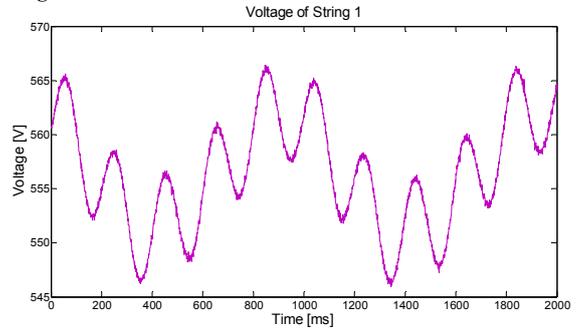


Fig. 7. Voltage of string 1

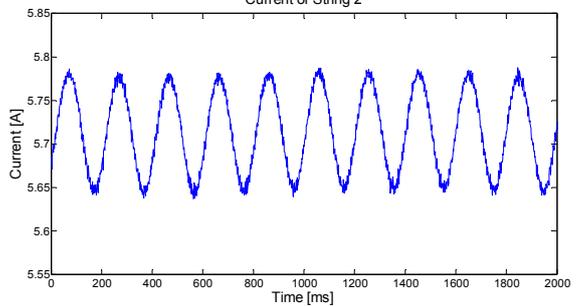


Fig. 8. Current of string 2

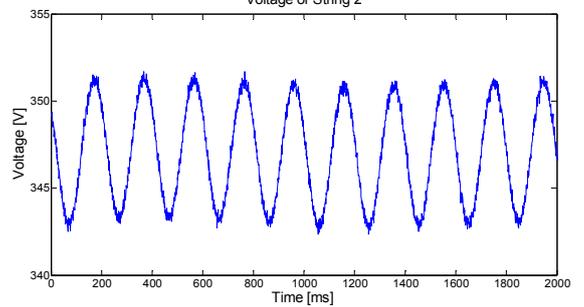


Fig. 9. Voltage of string 2

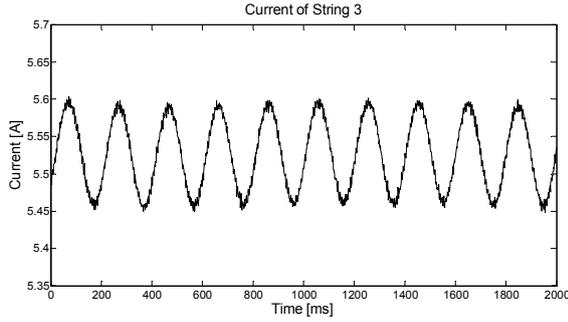


Fig. 10. Current of string 3

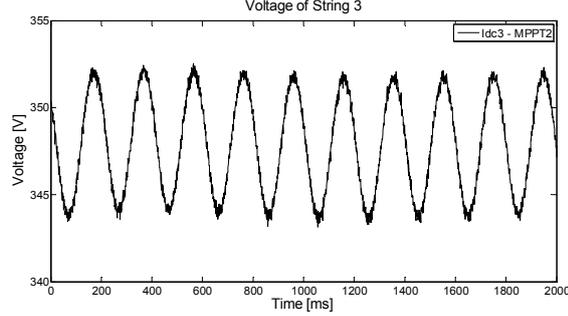


Fig. 11. Voltage of string 3

$$\eta_2 = \frac{P_{AC}}{P_{DC}} \quad (2)$$

$$\eta = \eta_1 \cdot \eta_2 \quad (3)$$

where P_{DC} is the DC electrical power, A is the total area of the panels, I is the solar irradiance, P_{AC} is the AC electrical power.

In Fig.12 the solar irradiance of a day of July 2011 is shown. In Fig.13 DC powers of the three strings and the total DC power is shown. In Fig.14 AC power is shown.

From these figures it can be seen that maximum solar irradiance is 1046 W/m^2 , the maximum DC power is 7.787 kW and the maximum AC power is 7.596 kW . In order to evaluate η_1 the parameter A must be known: it is equal to 78.82 m^2 .

For sake of clarity, the three efficiencies, i.e. η_1 , η_2 and η , and the total AC power, normalized to the maximum output power of the inverter, are shown as functions of day hour in Fig.15, while in Fig.16 as functions of solar irradiance.

As it could be expected, the maximum total AC power value is reached at the maximum solar irradiance value. In this point, η_1 is about 0.091 , η_2 is about 0.975 and η is about 0.088 . The efficiency η_2 is higher than 0.95 starting from 2 kW and its maximum is 0.985 at about 5 kW , that is the half of the maximum output power of the inverter. The maximum of η_1 is about 0.2 and it is reached when irradiance is about 70 W/m^2 and total AC power is about 1 kW .

Regarding η , it almost completely depends only on η_1 : its maximum value is about 0.19 and it is reached in correspondence of maximum value of η_1 . Other two phenomena have to be noted. The first is that at low irradiance values, η_2 , and thus η , become negative: this depends on the fact that the inverter, at switching on and

switching off, absorbs a power equal to about 70 W . The second phenomenon is that all the efficiencies have and hysteretic behavior with solar irradiance: this depends in the fact that the generated DC and AC powers have such behavior. In particular, at a certain solar irradiance value the values of the efficiencies are higher if the solar irradiance is decreasing than if the solar irradiance is increasing.

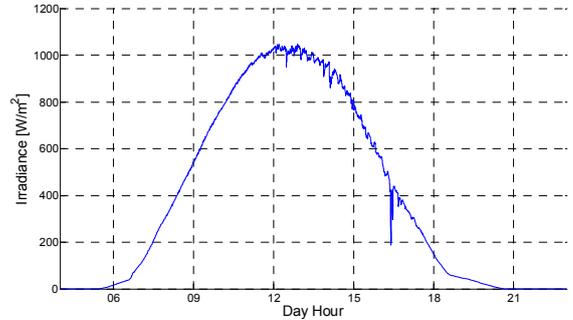


Fig. 12. Solar irradiance.

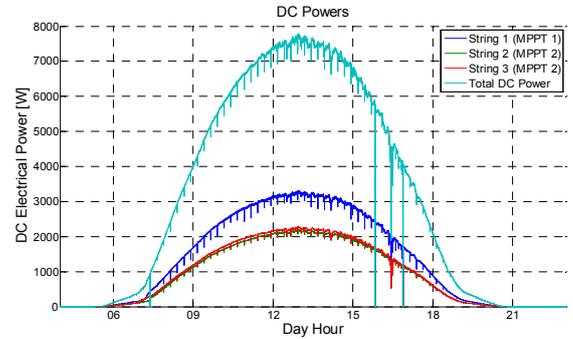


Fig. 13. DC powers.

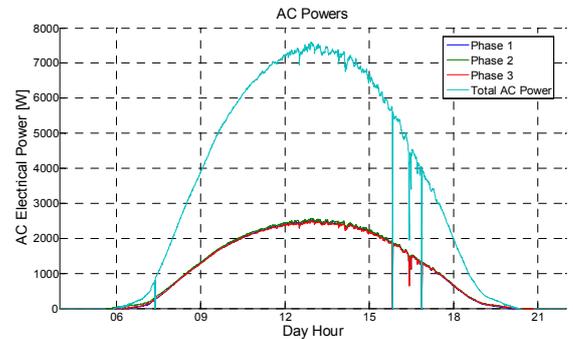


Fig. 14. AC powers.

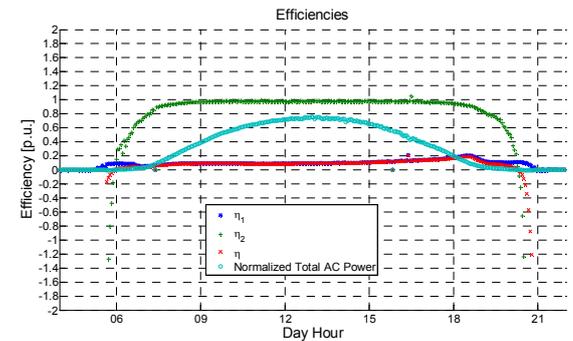


Fig. 15. Efficiencies as functions of day hour.

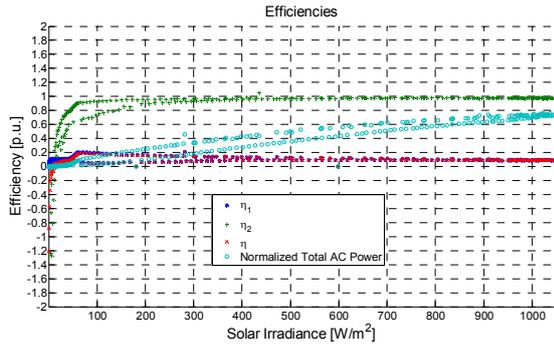


Fig. 16. Efficiencies as functions of solar irradiance.

3.3 Power quality analysis

In this subsection an analysis of quality of AC electrical power is shown. Fig.17 shows reactive power as function of active power: it is quite proportional to the active power, with a proportionality factor equal to -0.01814 VAR/W . Fig.18 shows power factor as function of active power: when active power is higher than 1 kW, the absolute value of power factor is higher than 0.9 and when active power is higher than 3 kW it is higher than 0.99. Fig.19 shows voltage total harmonic distortion (THDV) as function of active power: it practically not depends on active power, except for low active power values. In fact, as it can be seen from Fig.20, when active power is low current total harmonic distortion (THDI) is very high, reaching values as high as 190 %. This situation can be better understood from Fig.21 where THDV is shown as function of THDI: THDV clearly increases when THDI increases. THDI is high for low active power because in such situation the inverter does not work in its nominal operating conditions. Fig.22 shows voltage unbalance as function of active power: the two quantities are uncorrelated. Fig.23 shows current unbalance as function of active power: it is very high at low active power value and this verifies for the same reason for which the THDI is high at low active powers. Regarding harmonics, Fig.24 and Fig.25 show respectively voltage and current harmonic amplitudes. Voltage harmonic amplitude values are particularly at 3rd, the 5th and the 11th orders; anyway the 3rd, the 5th order harmonics are not induced by current, since their values are low in current. The 11th order harmonic has high value both in voltage and current: reasonably it is induced in the voltage by the current. This fact is particularly interesting: the network impedance evaluated at the 11th order harmonic could give useful information about the network status [6].

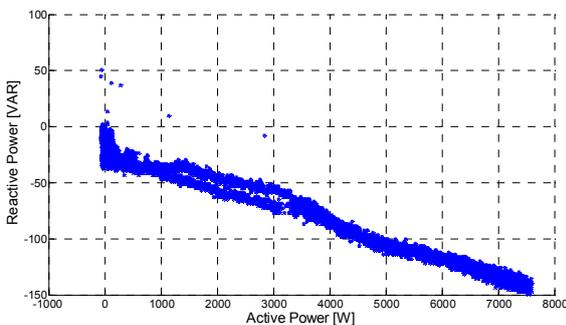


Fig. 17. Reactive power as function of active power.

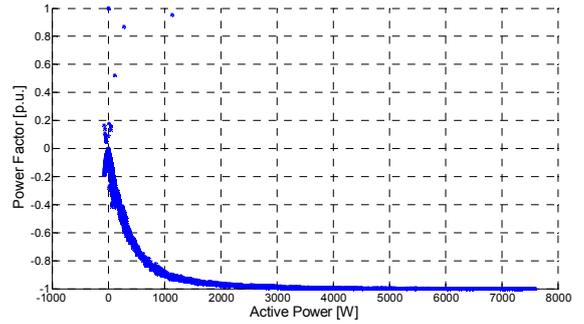


Fig. 18. Power factor as function of active power.

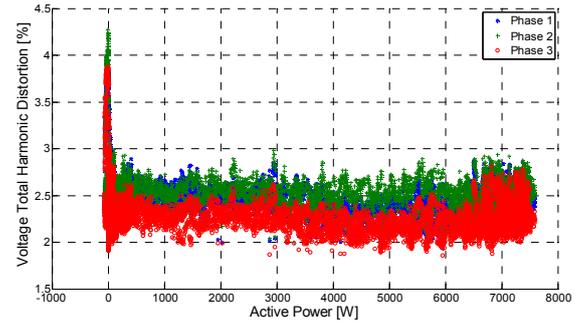


Fig. 19. Voltage total harmonic distortion as function of active power.

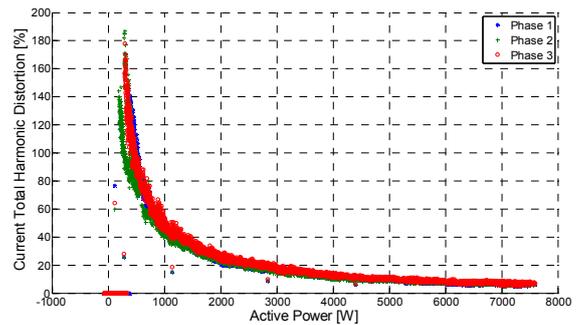


Fig. 20. Current total harmonic distortion as function of active power.

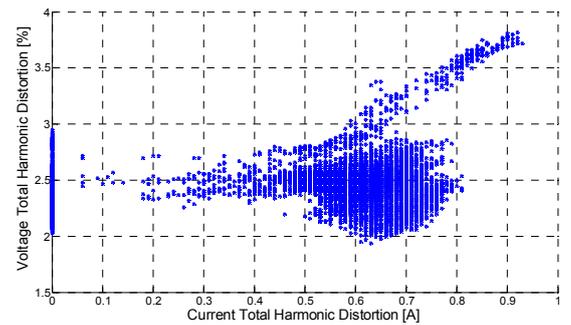


Fig. 21. Current total harmonic distortion as function of active power.

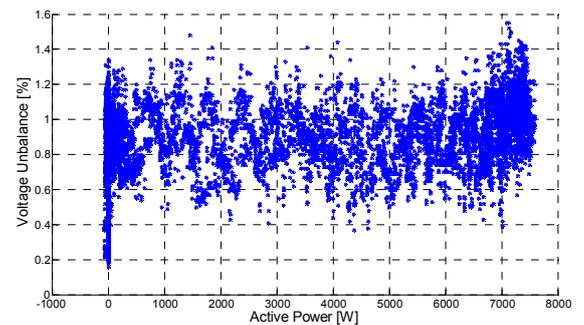


Fig. 22. Voltage unbalance as function of active power.

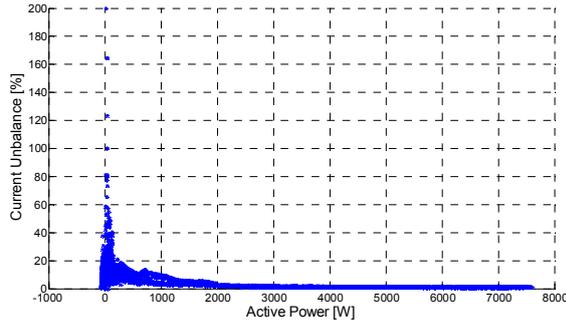


Fig. 23. Current unbalance as function of active power.

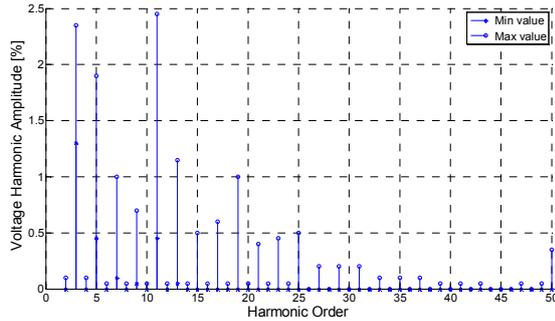


Fig. 24. Minimum and maximum values of voltage harmonics.

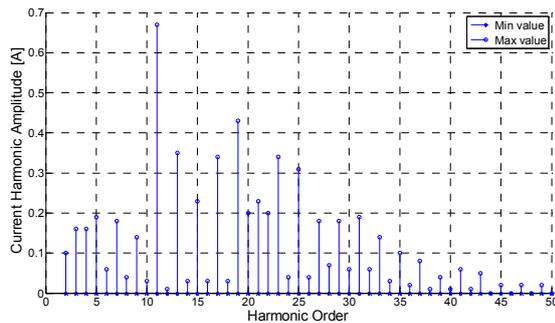


Fig. 25. Minimum and maximum values of current harmonics.

3.4 Shading test of a panel

In this subsection the results of test consisting in the shading of a panel is shown. A panel inserted in the String 1, connected to MPPT 1 has been completely shaded. Fig.26 and Fig.27 show respectively the voltage and power behaviors during the shading test. In the normal operating conditions voltage is about 580 V and power about 2040 W. After the shading, voltage reduces to about 550 V and power to about 1850 W. After the intervention of MPPT, voltage increases to about 570 V and power changes to 1830 W.

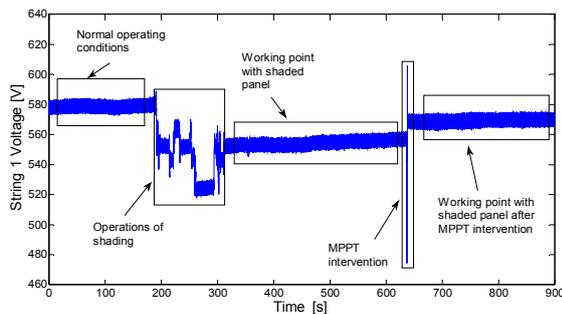


Fig. 26. Voltage behavior during the shading test.

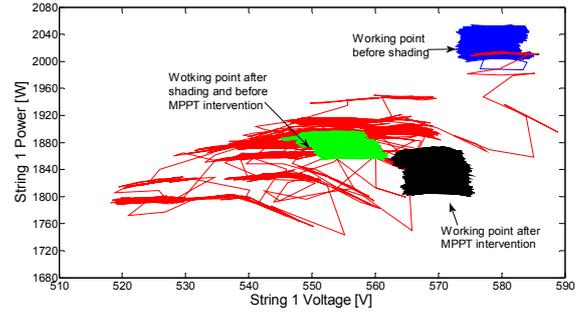


Fig. 26. DC power behavior during shading test.

CONCLUSION

In this paper a preliminary study about the electrical signature of a photovoltaic source has been presented. The description of the site and of the utilized instrumentation has been shown. A study about the efficiency of the system, that is the double energy conversion solar energy to DC electrical energy and DC to AC electrical energy, has been discussed. A analysis of the quality of the AC power has been performed. Finally a shading test on a module has been shown. The results obtained in this paper could be useful for future works, regarding the construction of a model for energy and malfunctioning forecasting.

REFERENCES

- [1] IEC EN 50160, "Voltage characteristics of electricity supplied by public distribution systems", 03/2000.
- [2] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, Std IEEEETM-1547, 2003.
- [3] Papaioannou, I.T.; Bouhouras, A.S.; Marinopoulos, A.G.; Alexiadis, M.C.; Demoulias, C.S.; Labridis, D.P.; "Harmonic impact of small photovoltaic systems connected to the LV distribution network", Electricity Market, 2008. EEM 2008.
- [4] A. Delle Femine, D. Gallo, C. Landi, M. Luiso, "Power Quality Monitoring Instrument with FPGA Transducer Compensation", IEEE Transactions on Instrumentation and Measurement, Volume 58, Issue 9, Sept. 2009 Page(s):3149 – 3158.
- [5] D. Gallo, C. Landi, M. Luiso, "Accuracy Analysis of Algorithms Adopted in Voltage Dip Measurements", IEEE Transactions on Instrumentation and Measurement, Volume: 59, Issue: 10 Publication Year: 2010, Page(s): 2652 – 2659.
- [6] Asiminoaei, L.; Teodorescu, R.; Blaabjerg, F.; Borup, U.; "Implementation and Test of an Online Embedded Grid Impedance Estimation Technique for PV Inverters" Industrial Electronics, IEEE Transactions on, Volume: 52, Issue: 4, Page(s): 1136 – 1144