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Experimental Assessment of the Waveform Distortion in Grid-Connected Photovoltaic System

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ABSTRACT: This paper provides an experimental observation study of 2.1 kW grid-connected photovoltaic (PV) system connected to(230v-50Hz) LV- grid, The considered system consists of 7 × 299 Wp polycrystalline PV modules and single-phase 2.1 kW grid-connected inverter. The power quality parameters at the inverter output side have been measured using Fluke 435- II Class A three phase energy and power quality analyzer. Several measurements carried out over a period of four days having different weather conditions and hence different solar radiation, The purpose of this paper is to present and evaluate the measurements of the power quality parameters obtained from the PV site such as voltage and current harmonics and their total harmonic distortion (THD). The gathered data analyzed in detail from the harmonic distortion viewpoint which is the most representative power quality indices. A modified Matlab/Simulink model is used to validate the field measurement results and to provide a better power quality performance, with the use of an LCL filter at the inverter terminal instead of the LC filter used with the actual inverter. The results of the waveform distortion analysis for harmonic currents and voltages are compared to the requirements of present power quality standards.

KEYWORDS: Power quality, Photovoltaic systems, Waveform distortion, Experimental analysis, LCL filter ,THD.

I.INTRODUCTION

In recent years, the trend towards renewable energy sources has increased for economical and environmental reasons[1]:

1. Photovoltaic (PV) systems have been one of the most developed renewable energy sources and registered a growing interest compared with other sources.
2. The economical barriers that typically limit the use of PV systems in the past, are in many cases reduced by significant regulatory or governmental incentives, towards larger use of PV solutions, especially when they are integrated into the layout of buildings.
3. The PV system contribute to reduce the load demand seen by the grid, and at the same time it guarantees non-interruptible supply to the local load[2].
4. PV provides an attractive method of power generation and meets the criteria of clean energy and sustainability , it represents a promising alternative source for the traditional energy sources that depend on fossil fuels, since the cost of energy produced from these sources is rising.
5. Photovoltaic systems used in the generation of electrical energy, either as Standalone systems or grid connected systems. Stand alone systems provided electricity in areas where there is no grid connection, while the grid-connected applications are used to provide energy in utility network.

PV grid connected systems utilize DC/AC inverters which convert the Direct Current (DC) generated by solar panels into Alternating Current (AC) and also to synchronize the output power with the system frequency. Power electronic components can affect the current and the voltage waveforms, were the current and voltage harmonics are strongly increased, and inject harmonic current directly into the grid[3].

For tie-grid inverters, its output should be compatible with the electrical characteristics of the grid to which they are connected, in a way that they don't affect the quality of the power system. The output voltage is synchronized with the grid voltage whereas the current should be a sinusoidal wave (as much as possible).

Due to the fast growth of photovoltaic (PV) installations for the resones mentioned earlier, concerns are rising about the harmonic distortion generated from PV inverters. The harmonic distortion induced by PV systems at the Point of Common Coupling (PCC)[4] ,should not exceed certain limits defined by the standard[4]-[6].

A useful tool to evaluate the harmonic content of a signal (i.e. grid current or voltage) is the Total Harmonic Distortion(THD), where the European standard EN 50160 [5] imposes a limit for the total voltage harmonic distortion equal to 8%, including up to the 40th harmonic. The IEC standard 61727 [6], which addresses the interface requirements between PV systems and the utility, imposes a limit for the total current harmonic distortion up to 5% . PV inverter whose harmonic current injected into the grid does not exceed these limits can be connected anywhere without any difficulty and special requirements. The problem of the quality of power provided by photovoltaic technology has to be addressed and advanced researches are still needed to overcome this problem as much as possible. The variable power flow due to the fluctuation of solar irradiance, temperature and other Environmental conditions as well as system design including the choice of power semiconductor devices, are some of the parameters that affect the power quality of photovoltaic systems. Good power quality translates into obtaining a sinusoidal voltage and current output from a photovoltaic system, in order to avoid harmonics, interharmonics, and eventually voltage distortion.

II. GRID CONNECTED PHOTOVOLTAIC SYSTEM DEECRIPTION

The photovoltaic system under analysis consists of 3 main parts, solar PV power panels, grid-connected inverter, and monitoring system. It's a grid connected system, with an installed capacity of 2.1 KW, being consisted of 7 polycrystalline silicon modules, YL300P-35b manufactured by Yingli Energy (China) . Fig 1 shows photo of the PV power panels involved in this study. The specifications of the PV module are summarized in Table1[7] . Table 2 shows the inverter specifications[8].

Fig.1. Photo of the PV array under consideration.

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Table 1: Yingli (YL300P 35b) PV module specifications at STC

Peak power (Pmax)	299,893 Wp
Maximum power voltage (Vmp)	36.7 V
Maximum power current (Imp)	8.17 A
Open circuit voltage (Voc)	46.3 V
Short circuit current (Isc)	8.77 A
Module efficiency (ηm)	15.4%

Table 2: ABB (UNO-2.0-I-OUTD-S) single phase grid-connected inverter specifications

Maximum input voltage (VDC max)	520V
Rated input voltage	(200–470) Vac
Rated output voltage	230 V
Rated output current	10.5 A
Rated output power	2000 W
Grid frequency	47–53 Hz
Power factor cos ϕ	0.99 (lead-lag)
Maximum efficiency	96.3%

The PV modules are arranged in one string being connected to ABB (UNO-2.0-I-OUTD-S) single-phase inverter, the inverter being tied by national grid to 0.23 KV. The technical data of inverter indicate a total harmonic distortion of the output current below 2%, and maximum output power of 2.2 KW.

III. EXPERIMENT SETUP

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 power quality analyzer Fluke 435- II, see Fig 2.

With regards to the evolution of harmonic content on the voltage and current waveforms, which is our major concern, the gathered data for the THDV and THDI are further analyzed and compared to the requirements of present power quality standards. For this, it has been continuously monitored the harmonic contents from March to June 2016.

Data for four days were selected in this paper to analyse the harmonic content for both PV's voltage and current, where these days have significant features related to the weather conditions, these days are 24th -27th of March 2016, the weather in these days was sunny for the first two days , cloudy and rainy at the 26th ,then partially cloudy at 27th of March . The monitored data acquired by the instruments Fluke 435 have been processed for time interval of 96 hours and with 5 minutes averaging interval.

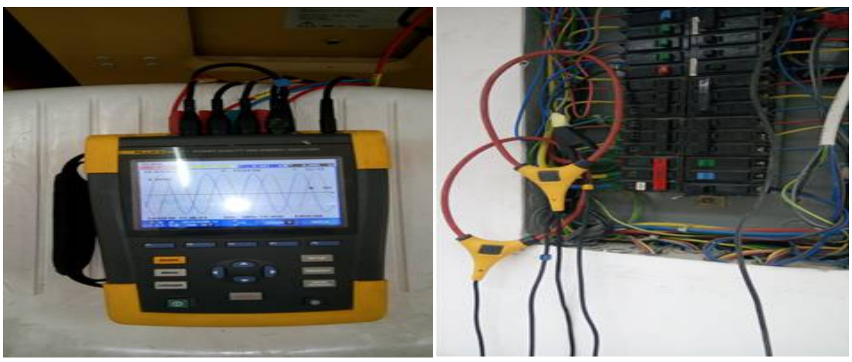

Fig.2. Three phase energy and power quality analyzer ,Fluke 435- II at the field measurement.

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Vol. 6, Issue 4, April 2017

IV. EXPERIMENTAL RESULTS

the measured data was examined carefully, and the results of the voltage and current can be summarized as follows:

1. voltage waveform:

The voltage waveforms in general are combatable with the standard, with a THD% ranging from (1- 3.2)% as an average values, the results are shown in Figs 3-5. An example of the inverter voltage signal is shown in Fig.3. While Fig.4 shows the THD of the Voltage versus the number of events, (i.e. number of events indicates how many times we had this value of THD), the results in this figure show that the THD varies from (1-3.2%) and the most THD had occurred, was about 1.25%. (it occurred more than 110 times). The relation between THD of the voltage and the output power from PV is shown in Fig.5, the result shows that they are independent of each other.

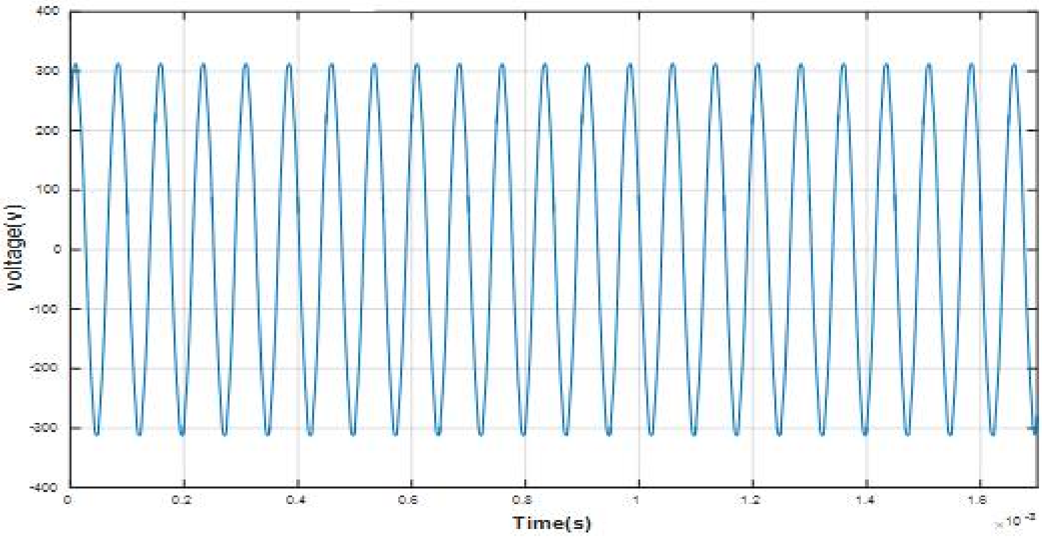

Fig.3. Output voltage of the PV inverter.

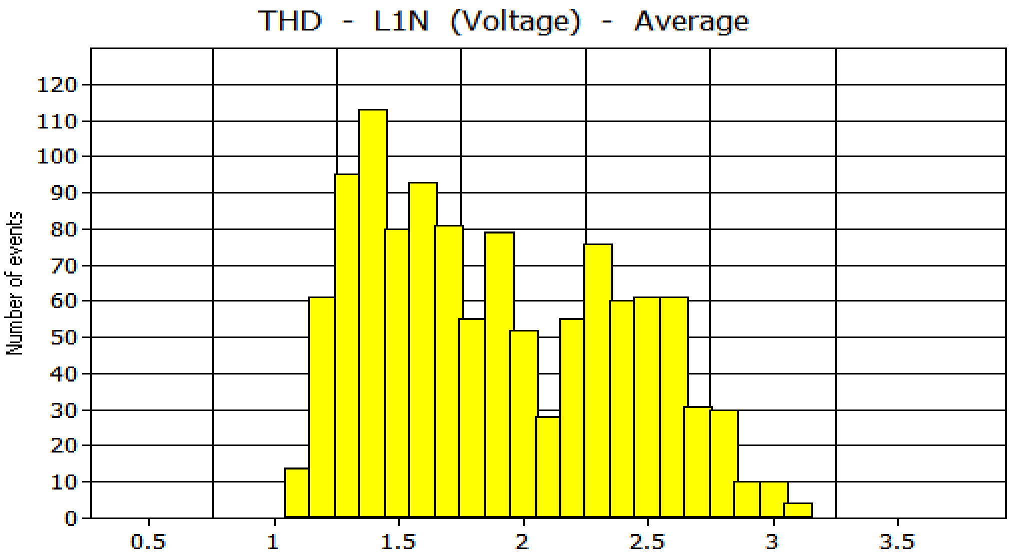

Fig.4. Histogram representation of the voltage THD values distribution

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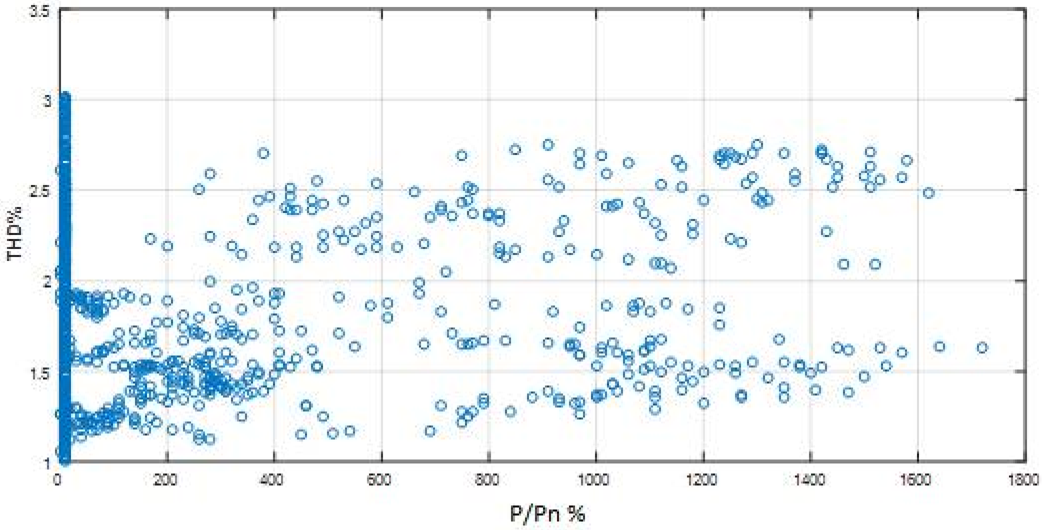

Fig.5. THD of Voltage versus PV power.

2. Current waveform:

the injected current from the inverter at the PCC is distorted , and the THD values for the current are ranging from(15.3-327.67)% , sample of the captured signals for the inverter current is shown in Fig.6

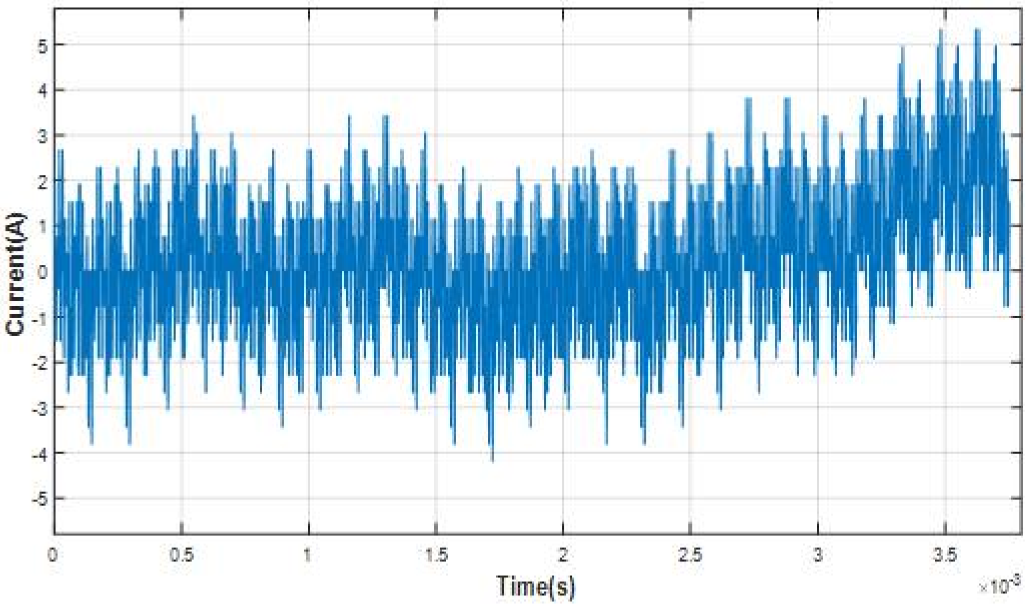

Fig.6. Inverter current from the PV system.

THD values during the measurement period ranging from (15.3- 327.67)% and concentrated around (15.3- 25) % as it is shown in Fig 7.

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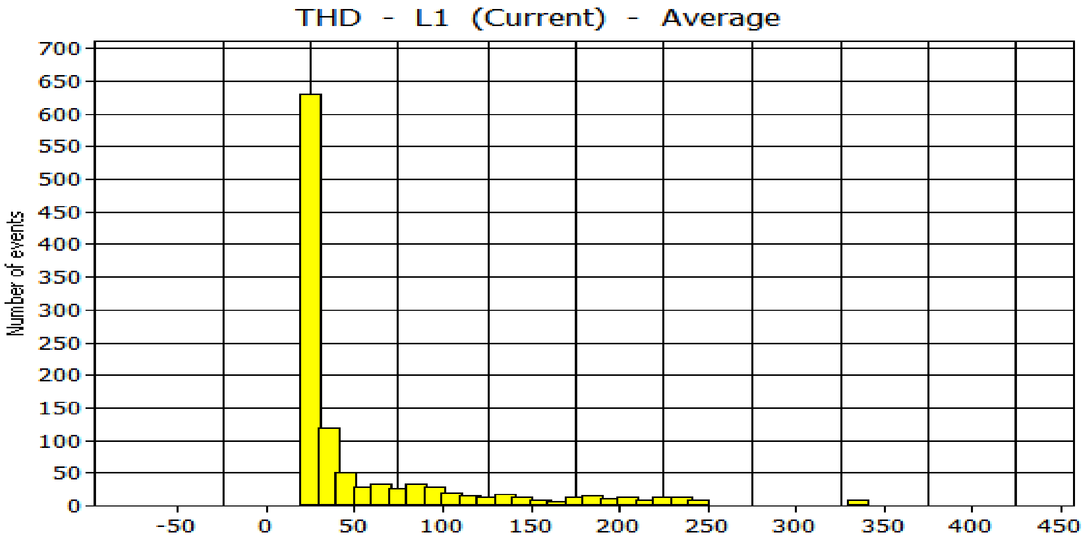

Fig.7. Histogram of the current THD values distribution.

Fig.8 shows the measured voltage and current waveforms, it was measured at 11:55 AM, when the output power from PV system considered to be at a peak value during the daylight hours, the current THD in this figure was around 15.5%, which is almost the lowest value was obtained in this study, as it is shown in this figure, the distortion in the current waveform is obvious compared to the voltage waveform, even with the lowest distortion in the current signal.

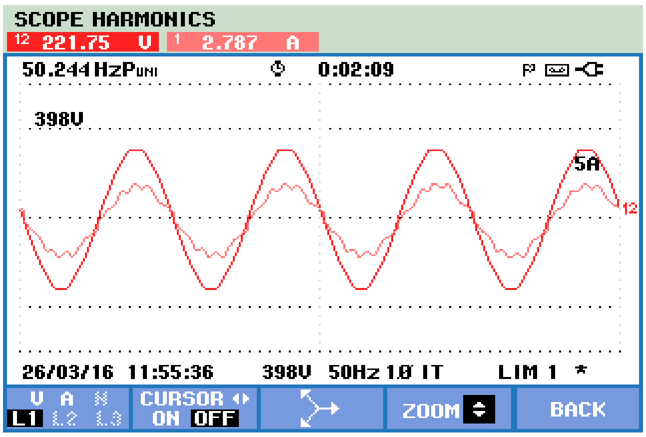

Fig.8. voltage and current waveforms with THD in current around its minimum value

The relation between THD of the current and the output power from PV system is shown in Fig.9, the PV power (P) represented as a percent of its nominal power Pn. This figure shows a strong dependency between the current THD and the PV power. As it is shown in this figure, the inverter current has a high value of the THD ranging from(50- 325)% when the power of the inverter is low (i.e. below 20%), this leads to have strongly distorted current signal, as the output power is increased the THD is decreased reaching a value up to 15.3%, but it is still exceeded the standard limits mentioned earlier (i.e. about 5%), another remark can be conclude from this figure, that the THD is slightly decreased for an output power varies from 50 to 80% of the nominal value, and the THD value is almost constant and

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approximately equal to 15.3% , so the output current must be filtered to reduce the harmonics in its signal to reach the standard limit.

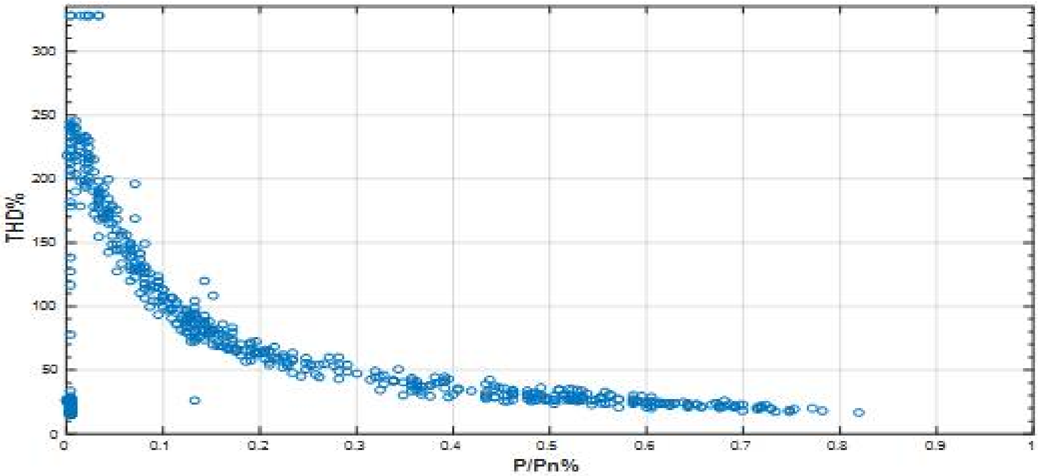

Fig.9. Current THD versus the PV power.

The weather condition affects the irradiance and thus causes fluctuation of the inverter power and hence affects its harmonic content. Fig.10(a) – Fig.10(f) show three days results extracted from the measured data, these days represent different weather conditions, even they are sequent days. Fig.10(a) shows the result of a sunny day, it was 25th of March, the result shows a gradually increasing in the electrical power produced from the inverter, reach about 1.8 KW, as the solar radiation increased during daylight hours, the impact of this in the THD value of the inverter current is shown in Fig.10(b), where there is a smooth fluctuation and almost constant value of the current THD when the power out of the inverter exceed 20% of its nominal power, even though this value is exceeding the limits as seen in the same figure. In 26th of march the weather was cloudy and rainy, the PV system produced less power as it shown in Fig.10(c), the maximum power was about 0.4 KW at the mid of the day , the fluctuation of the inverter power is low, since there is no significant change in solar radiation throughout the day because of the cloudy sky, this leaded to a higher THD value for the inverter current compared with the previous day, (i.e. less inverter power means high harmonic content in its current), the THD% of the current in this day is shown in Fig.10(d).

Finally at the 27th of march, the sky was partially clouded, and the sun appears from time to time. As it shown in Fig.10(e) ,the PV system power varying as the irradiance varying in that day, the fluctuation was very high, this fluctuation result in a noticeably THD variation for the inverter current as it shown in Fig.10(f). For all days the maximum value for the inverter current THD occurs with very small solar irradiance (at the sunset and at the sunrise) and due to the clouds, which is clearly shown in Fig.10 .

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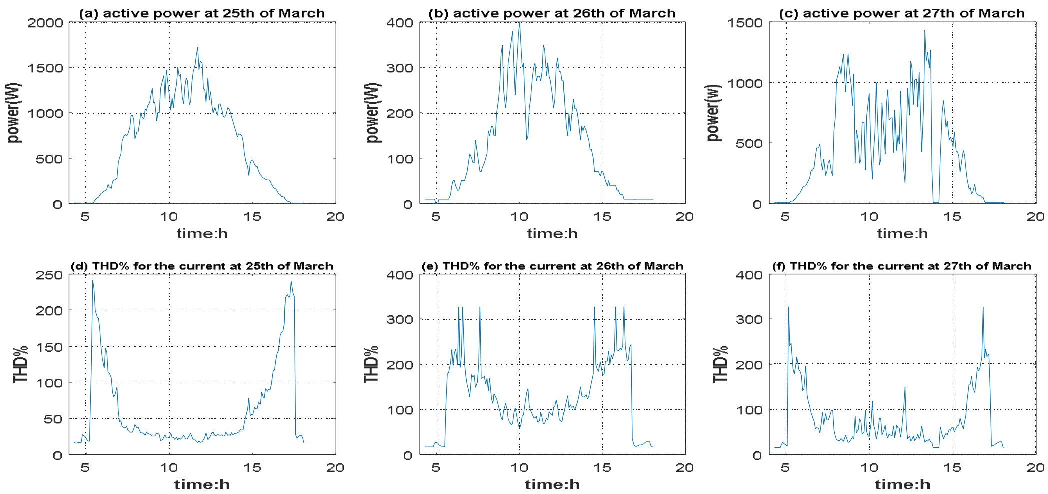

Fig.10(a-c) Measured PV power, (d-f) current THD of three days 25th , 26th and 27th of March 2016, sunny, cloudy and partly cloudy days respectively.

VI. L, LC AND LCL INVERTER FILTER TOPOLOGY

The inverter is one of the important equipment of the grid-connected PV system, and as a switching mode power electronics converter, the inverter will produce plenty of high frequency ripple current during normal operation. If this current is not filtered adequately, it will decrease the power quality, even produce Electromagnetic Interference (EMI) to other electrical and electronic equipments. So the filter is necessary for the PV system[9]. Fig.11 shows the block diagram for the major elements of a PV system including the line filter (filter between the inverter and the grid) .

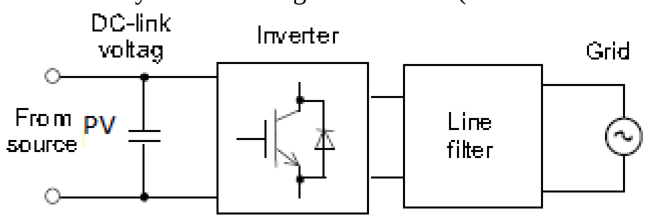

Fig.11. PV grid connected system.

The output filter helps in reducing the harmonics content in the generated current caused by semiconductor devices switching[10].There are various types of filters, the simplest one is the L filter, which consists of an inductor connected to the inverter's output, due to the cost and the disadvantages of using inductor in control devices, various combinations of inductor and capacitors like LC or LCL can be used.

The L-filter is the first order filter with attenuation 20 dB/decade over the whole frequency range. Therefore the application of this filter type is suitable for converters with high switching frequency, where the attenuation is sufficient. On the other side inductance greatly decreases dynamics of the whole system converter-filter, the L- filter is seen in Fig.12 (a).

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Vol. 6, Issue 4, April 2017

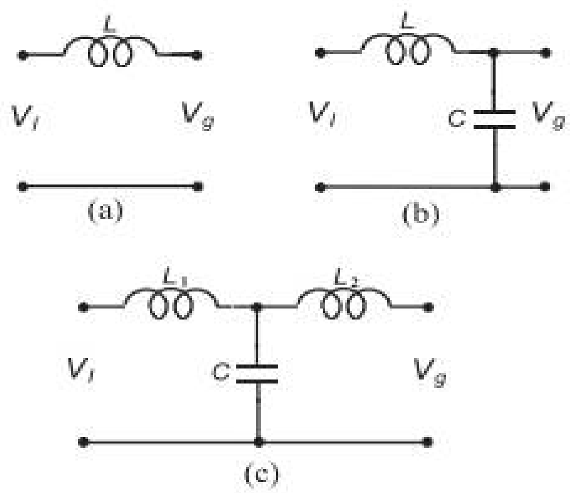

Fig.12. Basic filter topologies

The LC-filter in Fig.12(b) is a second order filter and it has better damping behaviours than L-filter, this simple configuration is easy to design and it works mostly without problems. The second order filter provides 12 dB per octave of attenuation after the cut-off frequency f0 , it has no gain before f0 , but it presents a peaking at the cut-off or resonant frequency f0.

The design of the filter is a compromise between the value of the capacity and inductance. The high capacity has positive effects on the voltage quality. On the other hand higher inductance value is required to achieve demanded cut-off frequency of the filter. Connecting system with this kind of filter to the supply grid, the result is that the resonant frequency of the filter becomes dependent on the grid impedance and therefore this filter is not suitable, too

The attenuation of the LCL-filter is 60 dB/decade for frequencies above resonant frequency, therefore lower switching frequency for the converter can be used. It also provides better decoupling between the filter and the grid impedance and lower current ripple across the grid inductor. Therefore LCL-filter fits to our application as a PV system inverter[10][11]. The LCL filter is shown in Fig.12(c) it has a good current ripple attenuation even with small inductance values. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter. The Important parameters of the LCL filter [12]-[13] are cut-off (resonance) frequency, inverter-side inductor, grid-side inductor and the capacitor, these parameters are calculated using equations from(1) to (6).The cut-off frequency of the filter must be minimally one half of the switching frequency of the converter, because the filter must have enough attenuation in the range of the converter's switching frequency. The cut-off frequency must have a sufficient distance from the grid frequency too, as explained in equ (2).

$$w_{res} = \sqrt{\frac{L_1 + L2}{L1L2Cf}} \quad (1)$$

$$10\,fg < f_{res} < 0.5\,f_{sw}. \quad (2)$$

$$L1 = \frac{V_{DC}}{6\,f_{sw}\Delta I_{L\max}} \quad (3)$$

$$\Delta I_{L\max} = 0.1 I_{\max} \quad (4)$$

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Vol. 6, Issue 4, April 2017

$$I_{\max} = \frac{P_n\sqrt{2}}{3V_{ph}} \quad (5)$$

$$L2 = rL1 \quad (6)$$

Where:

$f_{res} = \frac{1}{2\pi} w_{res}$, is the resonance frequency.

f_g : is the grid frequency.

f_{sw} : is the switching frequency.

L1 : is the inverter-side inductor.

L2 : is the grid-side inverter.

C_f : is the filter capacitor.

V_{DC} : is the DC link voltage.

$I_{\max}$: is the maximum current ripple at the output of dc/ac inverter.

r : is the ratio between the inductance at the inverter side and the one at the grid side, this ratio equal (1) for optimum design, based on[14].

V.SIMULATING RESULTS AND DISCUSSION

Based on the measured results, there is a need for improving inverter current by reducing its harmonic content, this improvement may be achieved by using an LCL filter at the output of the inverter terminal instead of the LC filter that is used with the actual inverter.

First the PV system is simulated using MATLAB R2015b, without any filtering, the parameters of the real PV is applied, then an average day 24^{th} of march 2016 , is simulated based on the measured data at this day and the linearity between the incident on the PV modules and the output active power [15], where the measured output power of this day is converted as an input irradiance for the simulated PV system. The simulation result shows that the inverter current without filtering has a THD value ranging between (35% - 174%), when the input radiation varies as the same as it varies in the reference day (24^{th} of March), the relation between the current THD and the inverter power is shown in Fig.13, and the distribution of the THD% for the inverter current without filtering is shown in Fig.14.

By using the proposed topology of the LCL filter, the profile of the inverter current THD is shown in Fig.15, this figure shows a significant improvement of THD, since the value of the THD for the inverter current is now ranging from (1.84% -76%) and it goes to < 5% as the power reach 20% of its nominal value and remains within this range, which is valid for rated power conditions according to [4], [16]-[17]. Fig.16 shows the distribution of the THD% for the inverter current after filtering, which shows that most of the time the THD is below 5%.

By performing of the Fast Fourier Transform(FFT) at the rated power condition(i.e. this mean applying the standard irradiance 1000 W/m2, at the input of the simulated PV system), for 10 cycle of the simulated inverter current, the result of it before and after filtering are shown in Fig.17 and Fig.18 respectively, where the THD% for the inverter current before filtering is 9.10% , and it reduced to 1.52% after filtering which is compatible with the standard[4].

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Vol. 6, Issue 4, April 2017

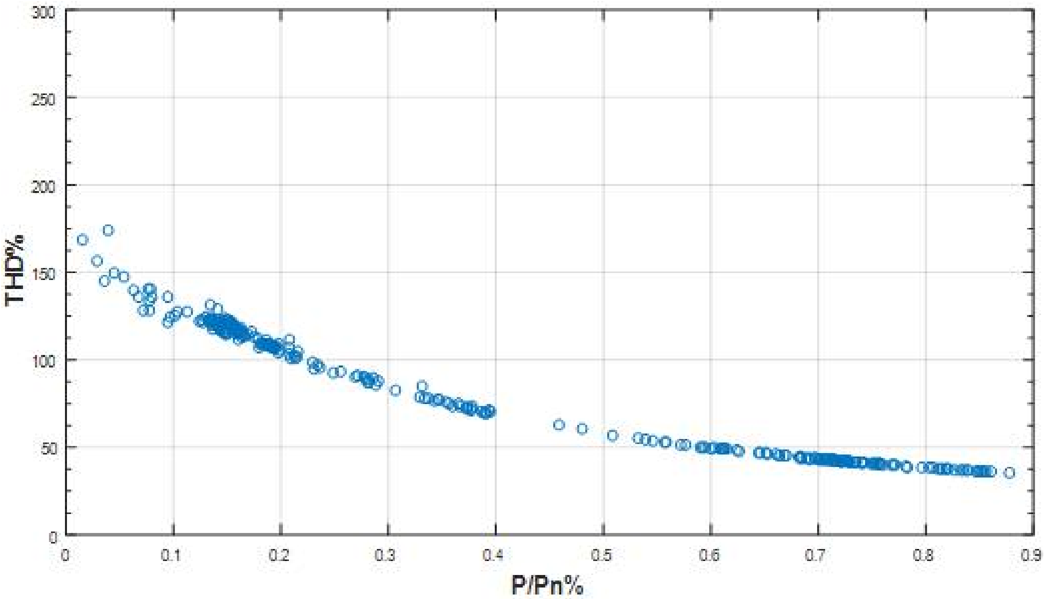

Fig.13. THD% and the active power trend for our simulation without filtering,
THD range(35-174)%,active power range(0.032 - 1.84353) KW.

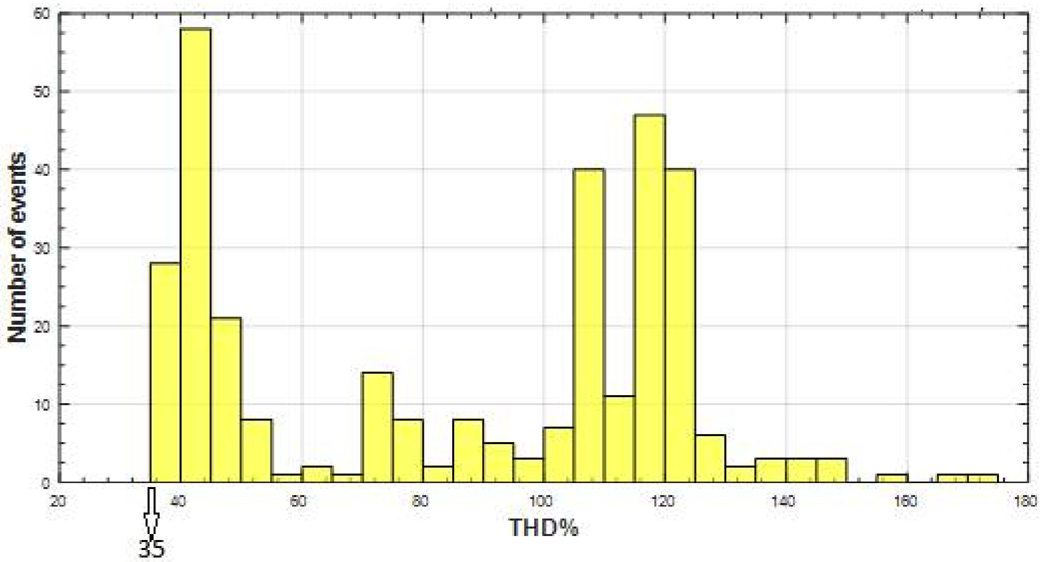

Fig.14 Histogram representation for the THD% of the simulated inverter current without filtering

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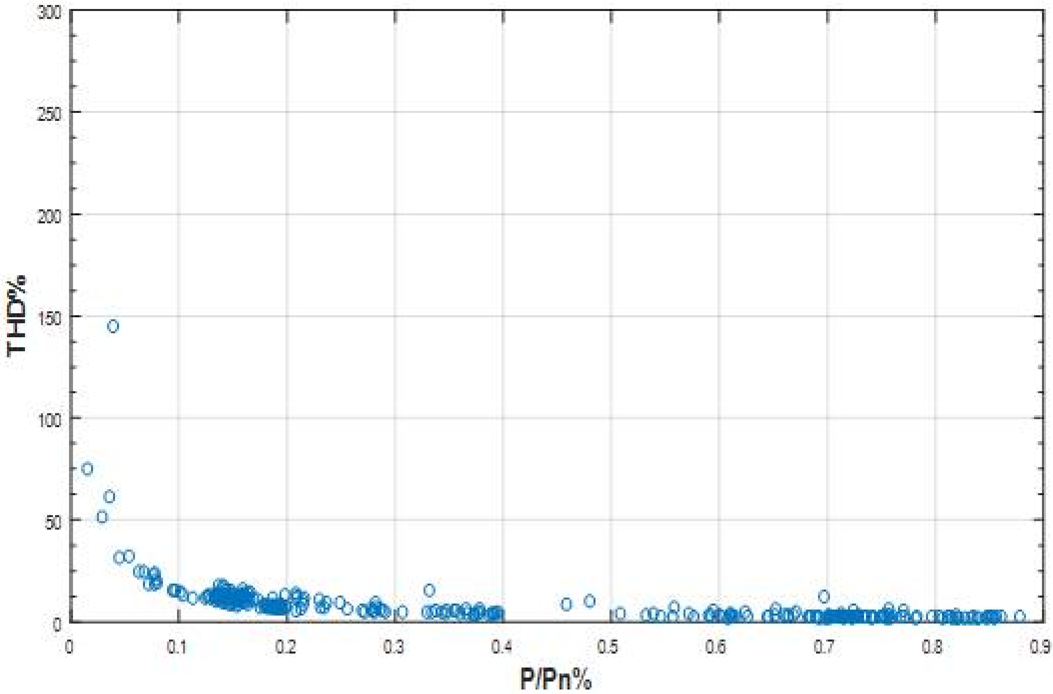

Fig.15. THD% and the active power trend for our simulation after filtering, THD% range(1.8-145),active power range (0.032 - 1.84353)KW.

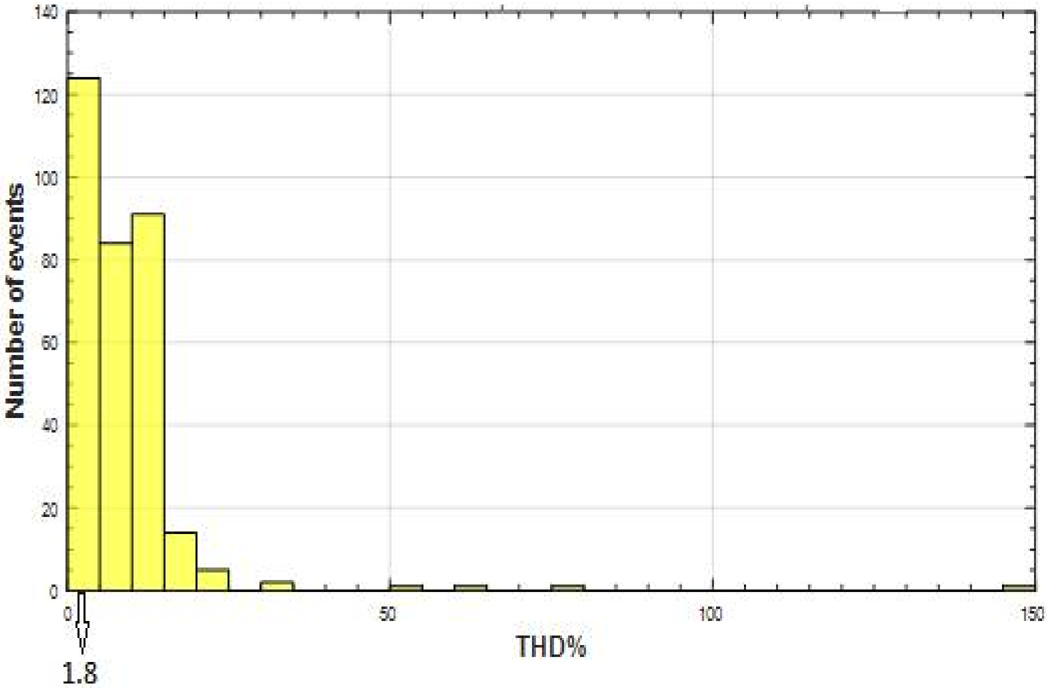

Fig.16. Histogram representation for the THD% of the simulated inverter current after filtering

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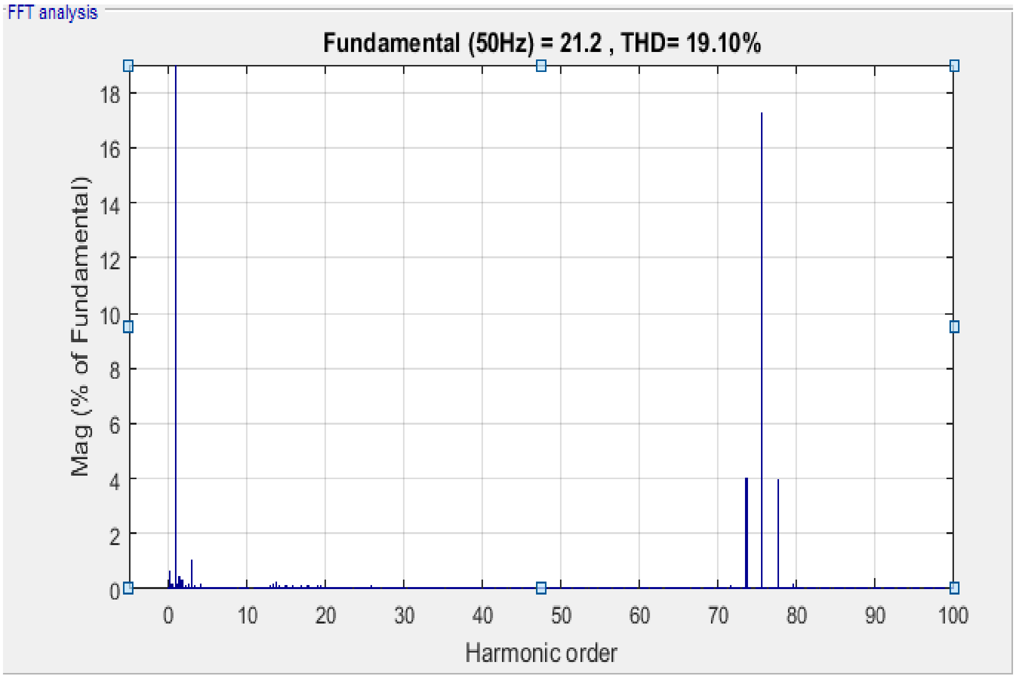

Fig.17. Sample signal of 10 cycles for the simulated inverter current before filtering with their FFT analyses.

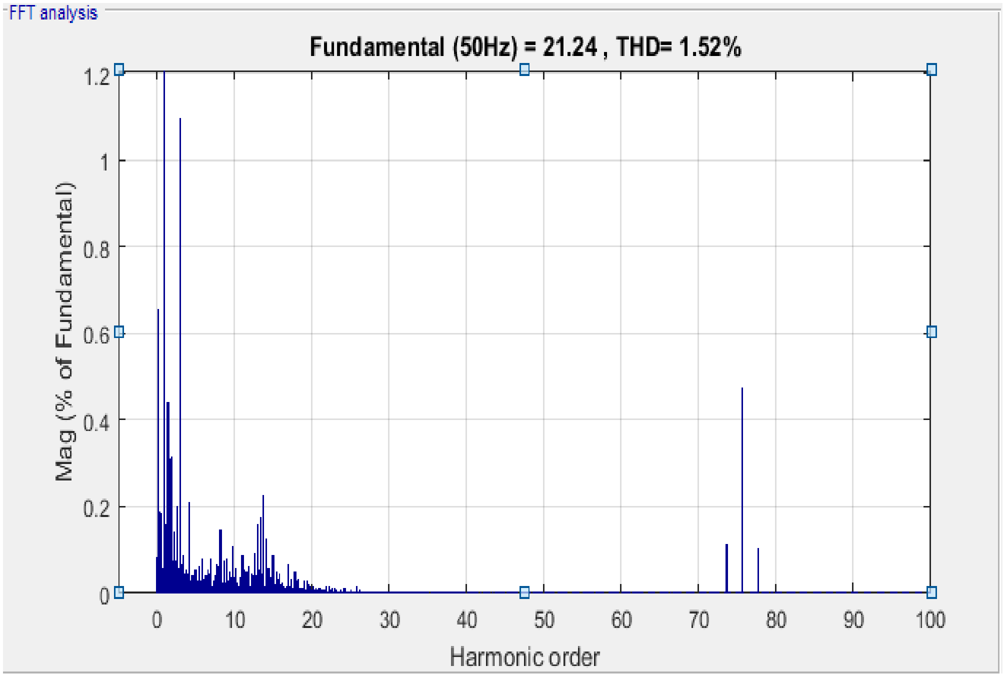

Fig.18. Sample signal of 10 cycles for the simulated inverter current after filtering with their FFT analyses.

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VI.CONCLUSION AND REMARKS

This paper analyzes the performance of a PV system connected to grid, by studying the effect of solar irradiation on the output power, current and voltage THD, three different scenarios have been considered ,namely, ’’sunny’ ’,’’cloudy’’ and’’ partially cloudy’’ days ,to represent irradiance variation and its effect on the power quality measurements. It has been found that a low solar irradiance has a significant impact on the power quality of the output of the PV system using the THD values as a first indication on the impact of the PV system operation on the harmonics. The behaviour of the THD of the currents during our assessment time (i.e. daylight hours) ,clearly shows that cases with high values of THD are limited to the periods with very small solar irradiance (at the sunset and at the sunrise) and to the effects of passing clouds, while the THD is relatively small when there is relatively high solar irradiance. The result shows that voltage THD of measured voltage signal is independent of the generated power or the fluctuations of solar irradiance. The results of the on-site measurements indicated that the voltage THD value is almost below the maximum permissible limit imposed by the regulations . On the other hand, the current THD value is always exceeded the maximum permissible limit of 5% . A proposed model for the PV system using an LCL filter at the inverter output terminal is Simulated based on an average day irradiance variation, and result in a significant improvement in the THD profile, so this model can be used to design an inverter with better power quality performance. A good design for the inverter ensures that at high generation level (i.e. output power of the inverter above 20% of its nominal power), the harmonic distortion is relatively low (<5%).

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