Power Quality Investigation of Single Phase Grid-connected Inverter of Photovoltaic System

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Abstract. There is a growing demand for renewable energy resources in countries all around the world. Among renewable energy resources, solar energy is a prominent and promising alternative to meet future electricity needs. Recently, the renewable energy regulations in Jordan have been modified to allow customers to install their own photovoltaic (PV) generators to cover their full energy consumption. This study investigated the power quality profile of single-phase grid-connected PV system in a typical Jordanian low voltage electrical system. The following electrical parameters were monitored: voltage, current, harmonics contents, total harmonics distortion (THD), active power, reactive power, and power factor. Detailed investigations and analyses were made.

Keywords*: energy; grid-connected inverter; harmonics distortion; photovoltaic; power quality.*

1 Introduction

Driven by economic and environmental concerns, there is a growing demand for renewable energy resources (RES) in countries all around the world. Among the available renewable resources, solar energy is a promising alternative energy source [1]. Jordan is blessed with an abundance of solar energy, which is evident from the annual daily average solar irradiance, which is one of the highest in the world, ranging between 4-7 kWh/m^2 [2]. Currently, Jordan is facing the challenge of meeting high growth in energy demand. High demand growth, dependence on fossil fuel sources, and dependence on unstable international interconnections have motivated the government to move towards renewable energy sources, mainly wind and solar energy.

Since 2010, renewable energy regulations have in been place. A recent modification allows customers to cover their entire energy consumption from renewable energy sources and achieve net zero energy [3,4].

Jordan is one of the leading countries in the region in integrating RES. According to Jordanian's renewable electricity road map 2019, the Jordanian

Received July 23rd, 2018, Revised January 9th, 2019 , Accepted for publication July 4th, 2019. .
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2019.51.5.1

government has a target of installing 1600 MW of RES (wind and PVs) in the national grid, which represents around 20% of the installed capacity, and to reach 30% of the installed capacity by the year 2022 [3,4]. Since the modification of the renewable energy regulations, many residential, commercial and industrial consumers have installed photovoltaic generators. The expected high penetration level of grid-connected PV systems (on the customer side, where PVs are installed at low voltage (LV) and medium voltage (MV) distribution networks) will change the distribution system configuration and necessitate additional operational requirements to maintain a stable and reliable distribution system [5].

Integration of such technologies may bring significant challenges to the electrical distribution system, such as issues with power quality, harmonics pollution, voltage level control, reversed power flow, and network protection [6-12]. Among these challenges, the impact of the integration of PVs in LV networks in the form of power quality issues and harmonics pollution is the most important. The switching behavior of inverters and other nonlinearities result in distorted injected currents and voltages. One of the commonly used methods in research to investigate these is extensive field or laboratory measurements [13]. The concept of a PV-solar farm as a static synchronous compensator (PV-STATCOM) to mitigate power quality issues is suggested in [14]. Reference [15] presents a study on the existence of voltage and current harmonics due to linear, nonlinear loads and the reactive power transferred between photovoltaic system, grid and load. A comprehensive analysis of harmonic resonance and the affecting factors in a distribution grid with solar photovoltaics is presented in [16]. In [17], a photovoltaic system model was developed in [18], using PSCAD software for power quality issue identification. Voltage changes and flicking performance of a PV plant were analyzed.

The dynamic performance of a grid-connected photovoltaic power system of distribution networks was investigated experimentally in [19]. The negative effects on power quality caused by the interaction between the grid and distributed power sources were analyzed in [20]. A comprehensive technique for analyzing harmonic resonance issues in megawatt grid-connected wind farms is presented in [21]. A case study on the impact of photovoltaic integration on voltage variation in a Brazilian secondary network distribution system was studied in [22]. The impact of large-scale PV generation on distribution system voltage regulation and voltage stability is reported in [23]

In this paper, a case study was conducted to deeply analyze the performance and behavior of a single-phase inverter PV system in a typical Jordanian low voltage system. Through extensive field measurements using a single-phase power recorder, several electrical quantities were monitored, such as active power, reactive power, power factor, total distortion harmonics (THD) for currents and voltages.

2 System under Study

A 2100 Wp polycrystalline type photovoltaic (PV) was installed at Mutah University campus as part of optional environmental actions. The project is located at the Prince Faisal Center for Dead Sea, Environmental and Energy Research (PFC-DSEER) as a pilot project within green university projects and as a seed for large-scale PVs that will be installed during 2019 to achieve net zero energy. Figure 1 shows a picture of the PV's panels. The PV system consisted of seven panels rated at 300 Wp each. Figure 2 shows a schematic diagram of the system. The inverter size was 2.0 kW. The measurements were taken with a single-phase configuration of a power quality analyzer.

Figure 1 Picture for photovoltaic panel at PFC-DSEER.

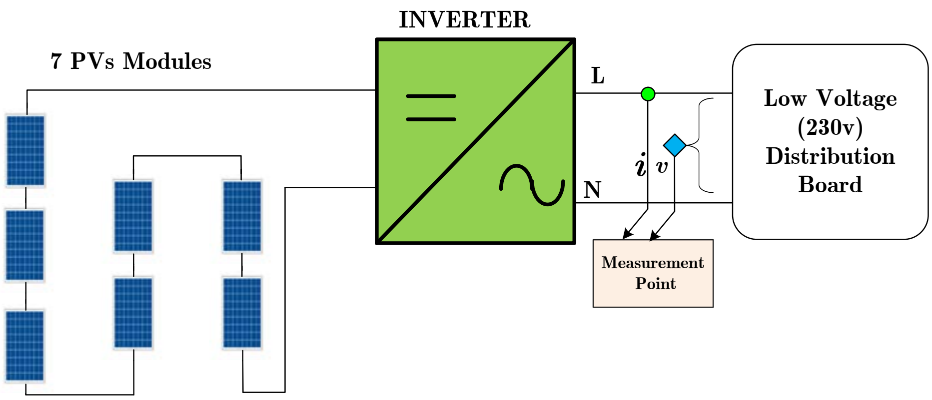


Figure 2 Schematic diagram of photovoltaic system.

3 System Measurement and Analysis

The system was monitored for different periods during the year 2017: a five-day period from December 1st to 6th, a five-day period from May 2nd to 6th, and a five-day period from September 14th to18th, here referred to as the first test period, the second test period, and the third test period, respectively.

3.1 Output Voltage and Output Current

Figures 3, 4 and 5 show the variation of output voltage and output current during the abovementioned test periods, respectively. The output currents reflect the typical sun irradiance profile. In the first test period, the recorded output voltage was varied between 219 V and {232.8 V and 228.1 V}. The former occurred on the second day (weekend day) and the later occurred on the fourth day (working day). The percentage increase in voltage in this period varied from 3.95% to 6.0% (this percentage refers to the base voltage of 230 V). Figure 4 shows the output voltage and current variation for the second test period. During the first two days (weekend days), the average output voltage increased from 221V to 235.9 V (6.4% increase) at the peak current of the PV system (at solar noon), while for working days the average output voltage increased from 219 V to 232.62 V (5.9% increase). The reduction in the voltage during working days was due to the effect of nearby loads.

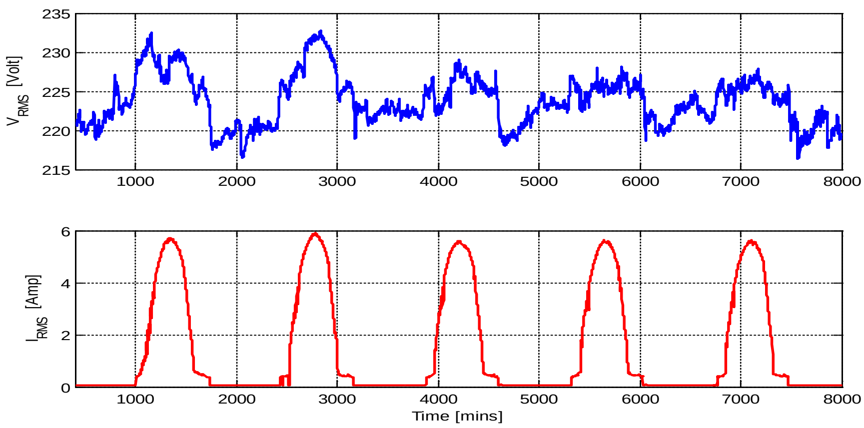


Figure 3 Variation of inverter output voltage and current for the first test period.

Figure 5 shows the variation of output voltage and current for the third test period, in which the voltage during operation of the inverter increased from 220 V to 232.5 V on the second day and reached 229.1 V on the fifth day. The voltage increased during this period from 3.95% to 5.4%. The key finding from these results is that the existence of a PV in a LV area (commercial area) increased the voltage by different values. In this study the voltage increased up to 6.0%. The range was within the acceptable range of voltage variation in distribution networks. The voltage fluctuation was within the operating range of voltage regulator devices in the distribution system (tap-changer and substation capacitor bank).

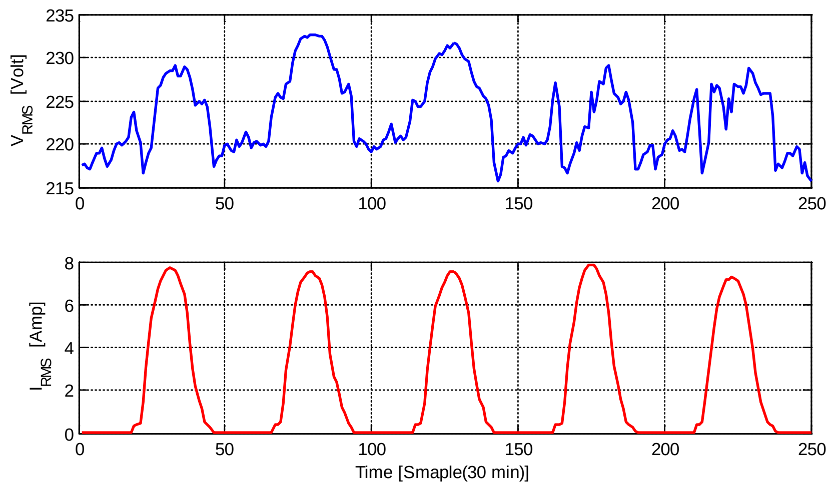


Figure 4 Variation of inverter output voltage and current for the second test period.

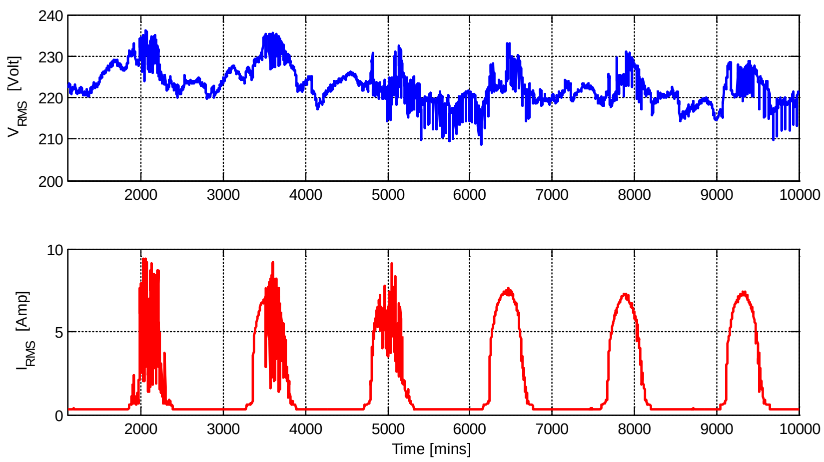
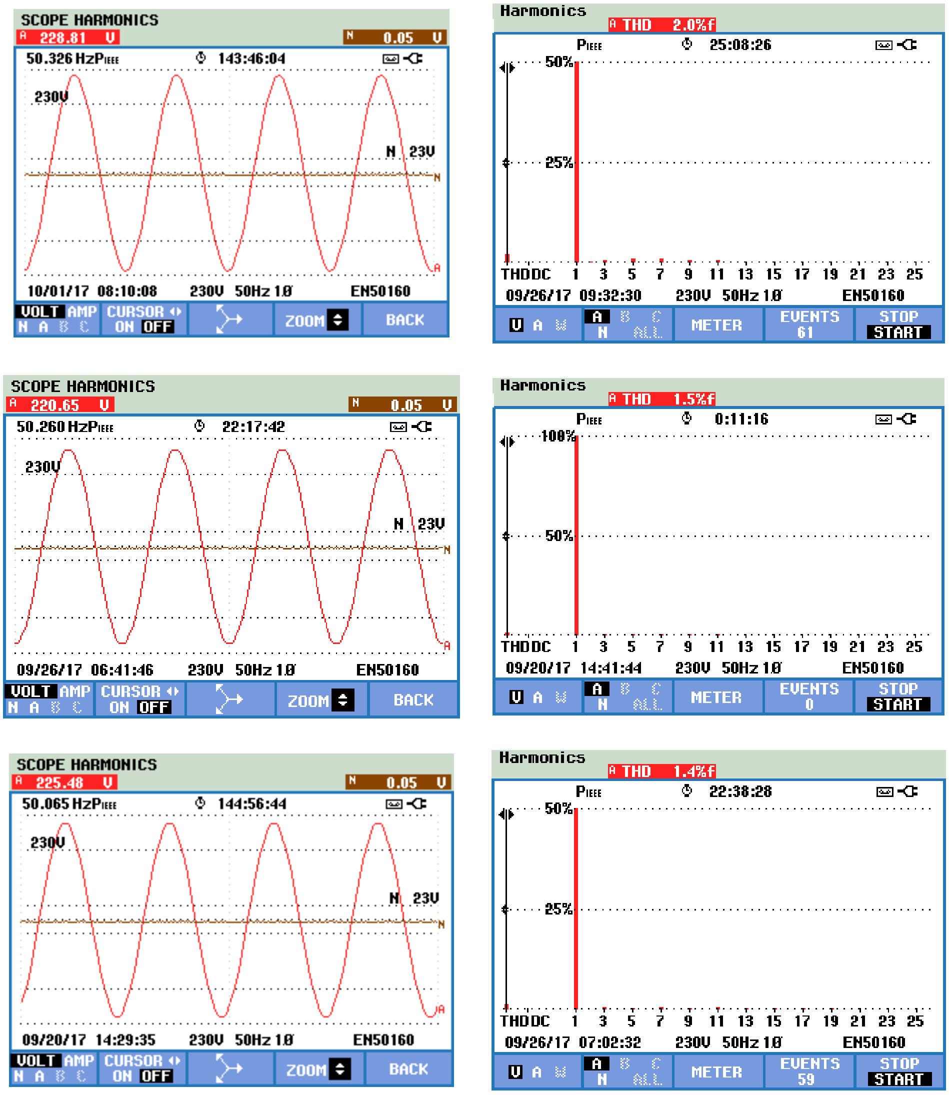


Figure 5 Variation of inverter output voltage and current for the third test period.

3.2 Harmonics Voltage

Figure 6 shows snapshots for voltage waveform, voltage THD and harmonics spectrum during the second test period. The same trend was observed for the other test periods. Meanwhile, it is clear that the dominant harmonics contents were the fifth, third and eleventh, respectively.



(a) Voltage waveform (b) Harmonics spectrum

Figure 6 Snapshot for (a) voltage waveform and (b) THD and harmonics spectrum.

Figures 7, 8 and 9 show the variation of total distortion harmonics voltage (THD_V) during the abovementioned test periods. The results in the three test periods showed a similar trend: the THD voltage decreased as the generated power from the inverter increased. The maximum value of THD_V (which occurred during the night) was less than 3%, which is within the acceptable level of international standards.

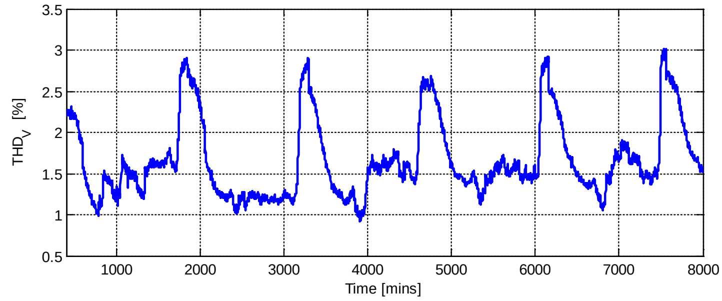


Figure 7 Variation of THD voltage for the first test period.

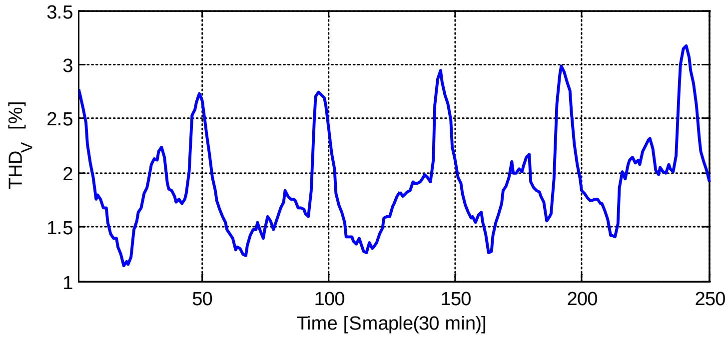


Figure 8 Variation of THD voltage for the second test period.

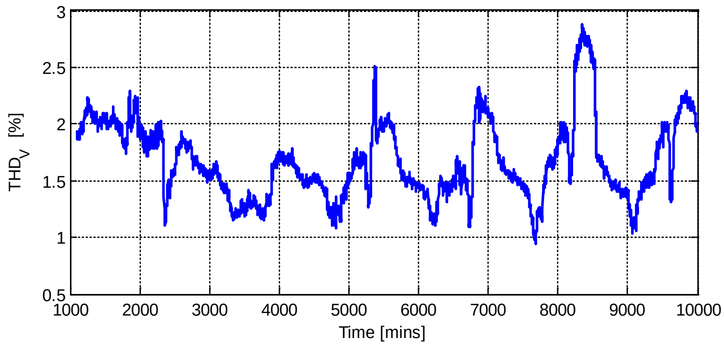


Figure 9 Variation of THD voltage for the third test period.

3.3 Harmonics Current

The total distortion harmonics current (THD_I) from the inverter was monitored. Figures 10 and 11 show snapshots of the current waveforms, the THD_I and the harmonics spectrum during the month of September 2017. These snapshots were selected to show the majority of operating conditions of the inverter (i.e. different irradiance levels). Similar trends were observed for the other two test periods. Meanwhile, it is clear that the dominant harmonics contents varied according to the operation points (irradiance level). Generally, the most dominant harmonics were 7^{th}, 9^{th}, and 11^{th}.

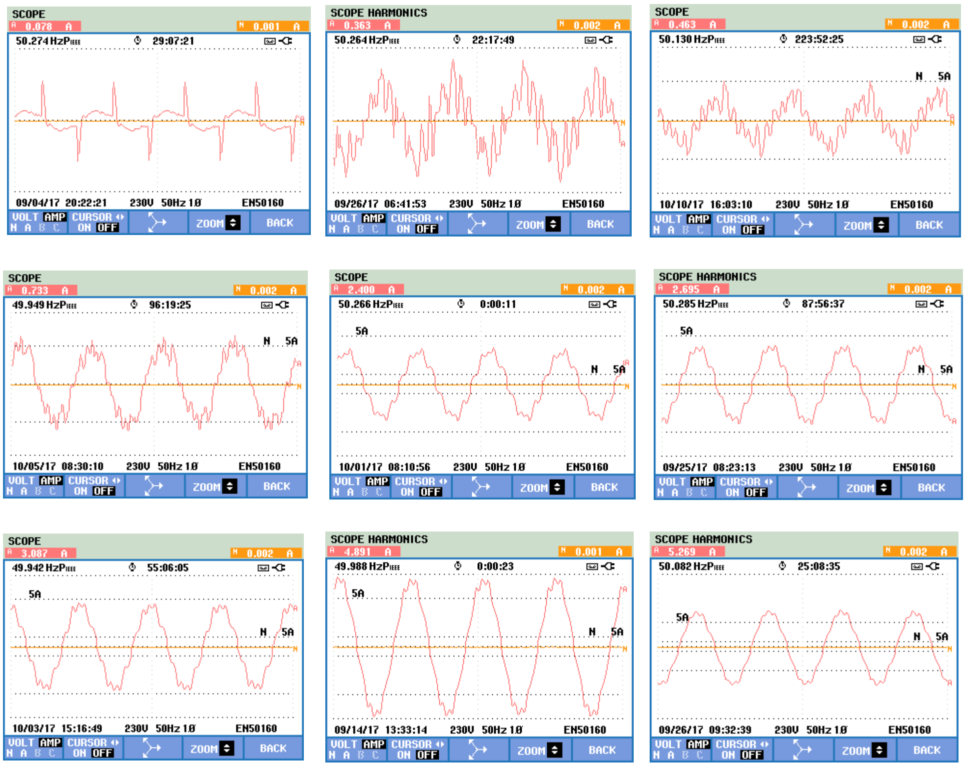


Figure 10 Snapshot of current waveforms at different time slots (different irradiance levels).

Figures 12, 13 and 14 show the variation of THD_I during the test periods. Figures 15, 16 and 17 show the relationship between the output current and THD_I. As can be seen, there was an inverse relationship between THD_I and the output current. The THD_I level was high at low output current (i.e. low irradiance level), in the early morning (sunrise) and evening (sunset). This value reached up to 70%. In the first test period, THD_I started to drop below 20% when the inverter started generating 2.0 Amp (corresponding to 23% of the inverter rating) and started dropping below 10% when the inverter generated more than 3.4 Amp (corresponding to 40% of the inverter rating). The same trend was observed for the second test period. During the third test period, the selected day was very cloudy and the THD_I dropped to less than 10% when the inverter started generating more than 50% of its rating.

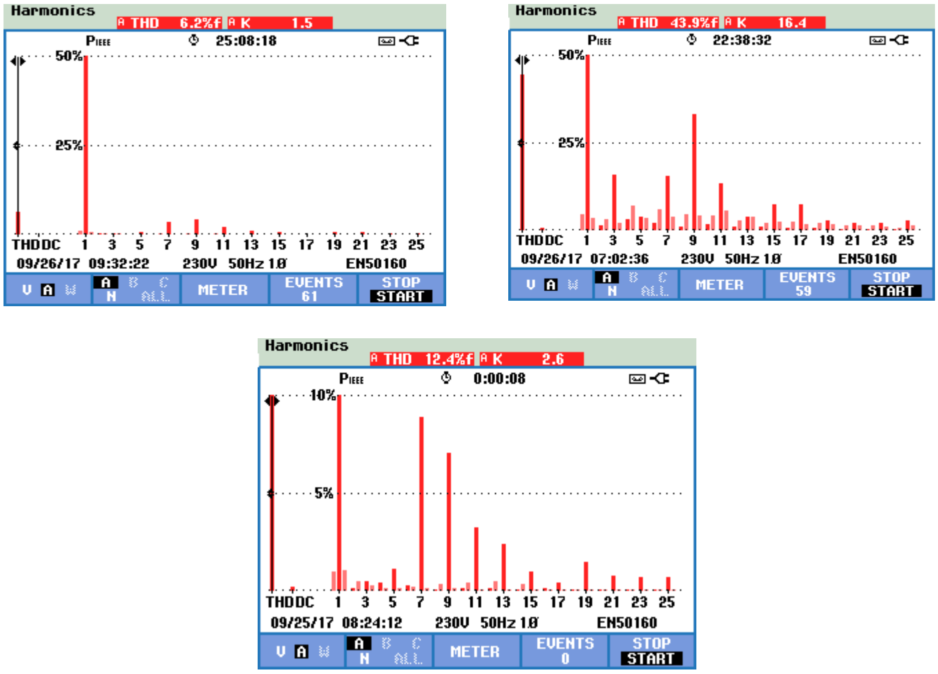


Figure 11 Snapshots for THD and harmonics spectrum at different time slots (different irradiance levels).

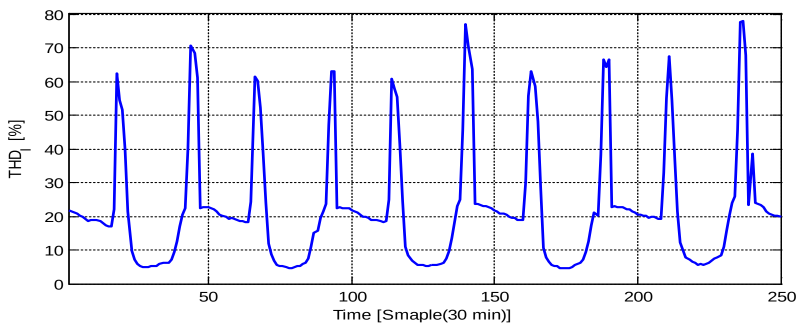


Figure 12 Variation of THD current during the first test period.

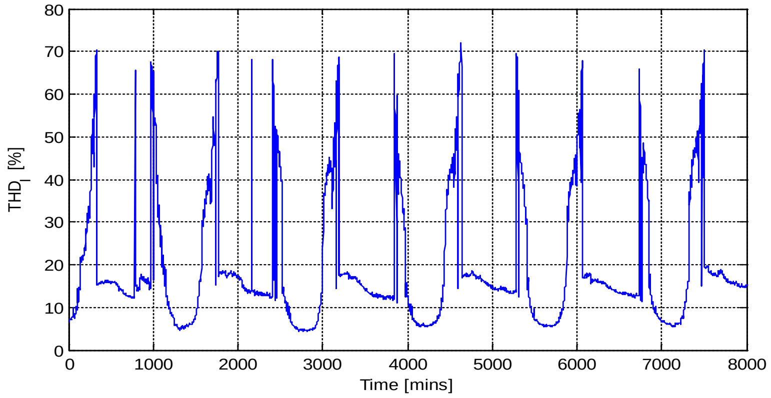


Figure 13 Variation of THD current during the second test period.

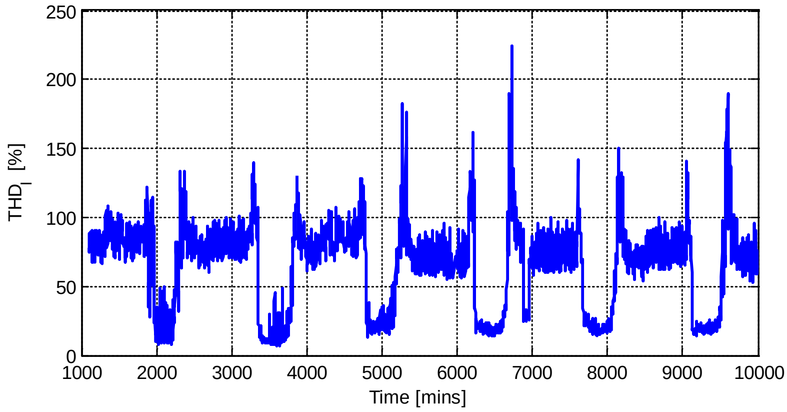


Figure 14 Variation of THD current during the third test period.

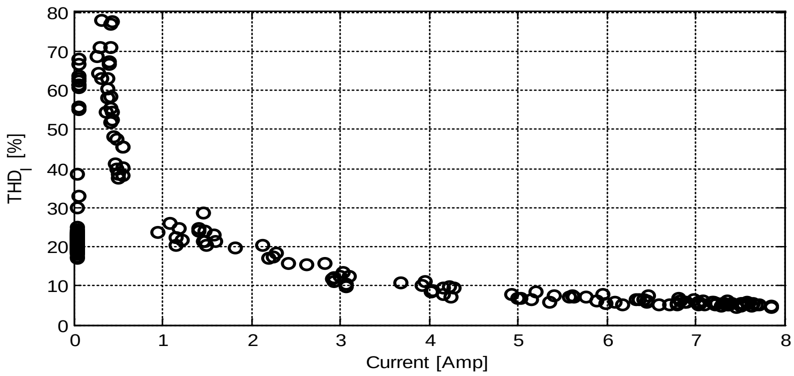


Figure 15 Relationship between THD_I and output current during the first test period.

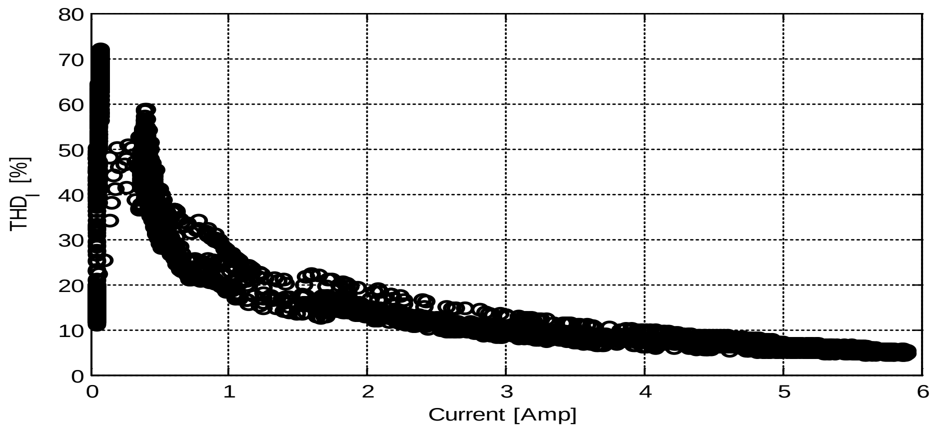


Figure 16 Relationship between THD_I and output current during the second test period.

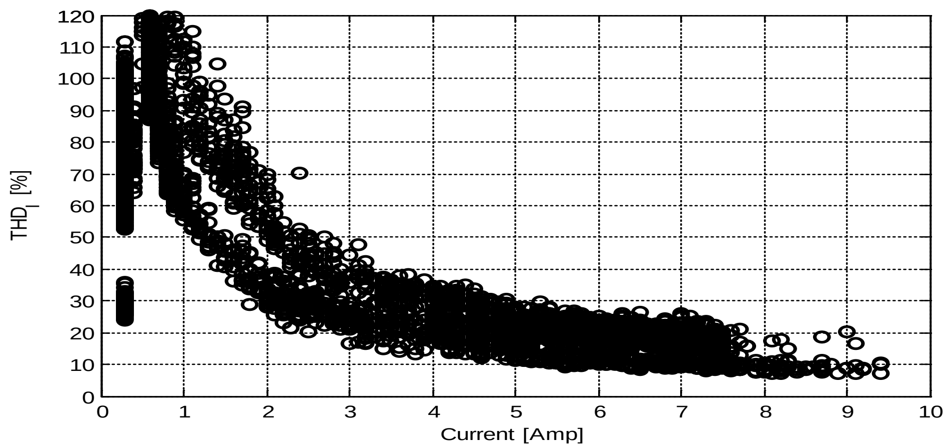


Figure 17 Relationship between THD_I and output current during the third test period.

Figures 18, 19 and 20 show the statistics for THD_I on the following selected days: May 5th, December 2nd, and September 18th. The statistics record shows that only 5% of the recorded readings were below 11% for December 2nd. On September 18th only 5% of the recorded readings were below 16.49%. For May 5th, 5% of the THD readings were below 5.01%. The average current harmonics contents in the three test periods exhibited the same trend; therefore only average current harmonics contents during the first test period were analyzed.

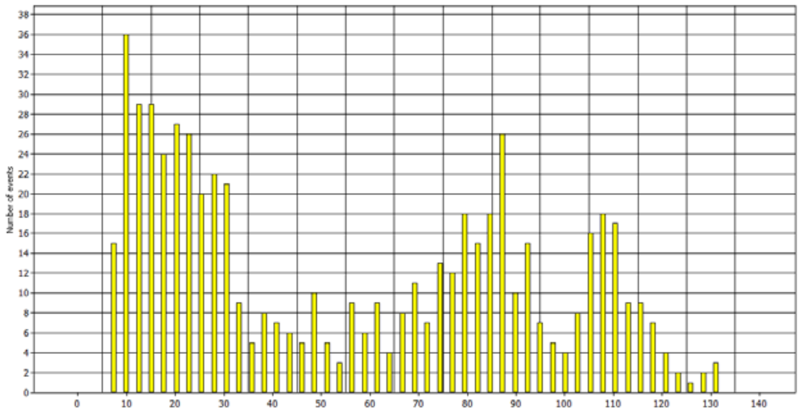


Figure 18 Statistics record for THD current for December 2nd 2017.

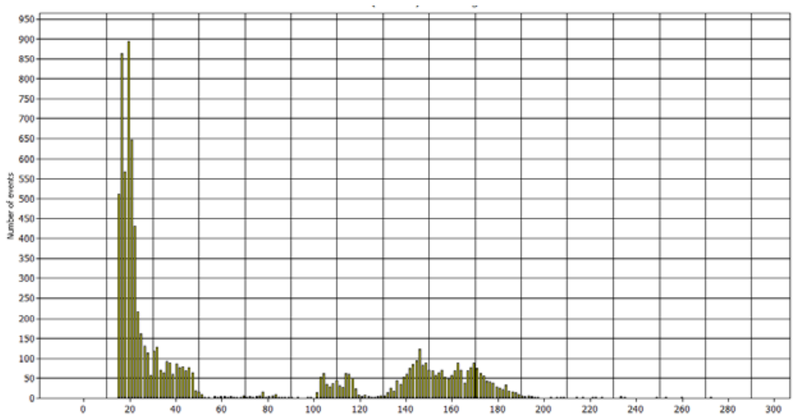


Figure 19 Statistics record for THD current for September 18th 2017.

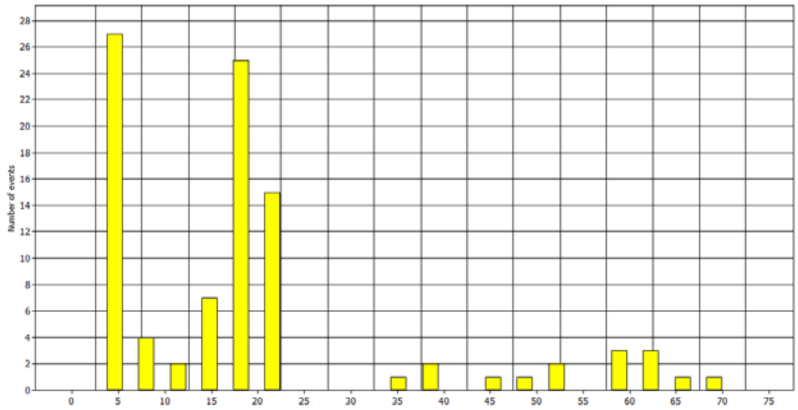


Figure 20 Statistics record for THD current for May 5th 2017.

Figure 21 shows the variation of the average current harmonics contents. The dominant harmonics were 3rd, 5th, 7th, 9th, 11th and 13th. The 3rd and 5th harmonics order decreased sharply when the inverter started picking up sunlight and they dropped to below 0.6% at peak power. A similar trend was observed for the 11th and 13th harmonics orders. The 7th harmonics order dropped to 3.76% while the 9th harmonics order dropped to 2.1% during the day. It is understood that the 7th and 9th harmonics orders have a large contribution to the THD_I value at both high and low irradiance levels.

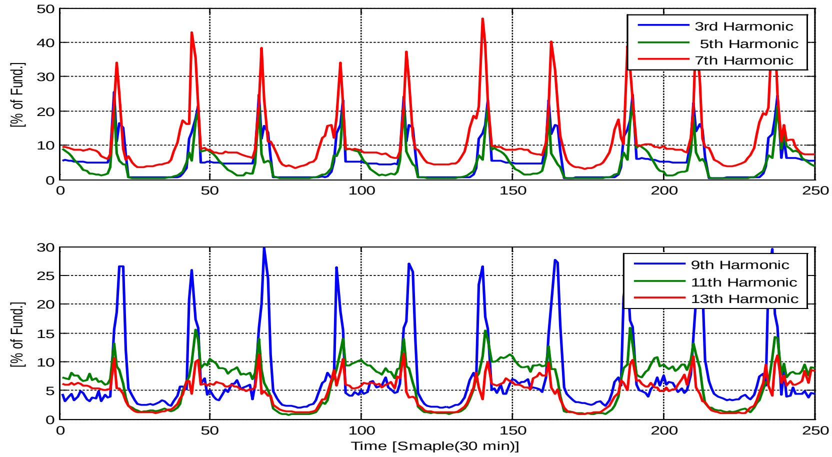


Figure 21 Variation of dominant current harmonics for the first test period.

3.4 Active, Reactive and Power Factor Profile

Figure 22 shows samples of the phasor diagram of current and voltage at different operating conditions during the month of September 2017. The studied inverter had been set to operate in unity power factor mode. It is clear that the inverter operated close to unity power factor at its rated power (the bottom group of the figures). As the irradiance level increased, the angle moved from 90 degrees to zero degrees at solar noon. At lower generated current (i.e. low irradiance), the angle reached 90 degrees. Such behavior can be attributed to the internal control system of the inverter, where under a low value of the fundamental current, which is reflected in lower active power, the controller is unable to track its value. The observed general trend of angle variation showed similar behavior during all the test periods in this study. It was also observed that during the night, when the inverter was requested to functionally operate, the inverter consumed active power (which is not normally the case for typical grid connected inverters, unless they are requested to operate as a STATCOM). This value is typically 1-2% of the inverter rating, whereas in our case it was 20 W.

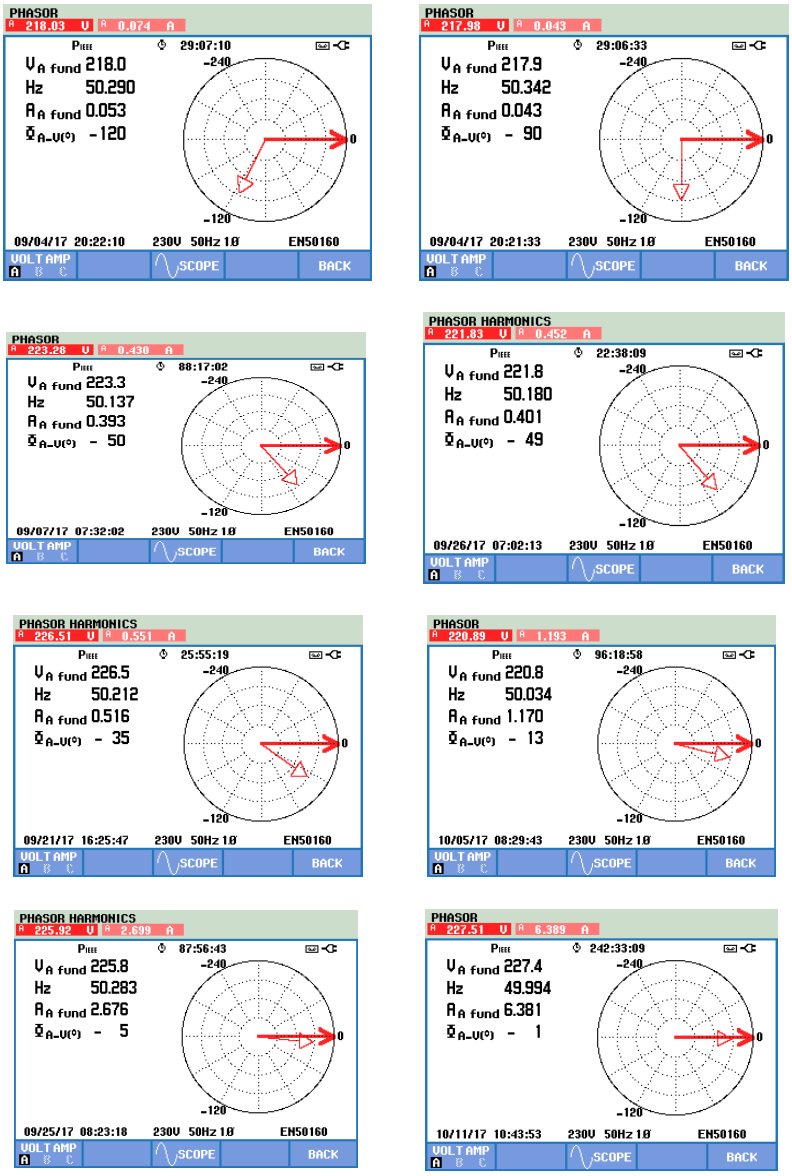


Figure 22 Snapshots of a phasor diagram of the output inverter current and voltage.

Figure 23 shows the profile of active power, reactive power and power factor during the period from May 2nd to May 6th 2017. The behavior shows steady variation during sunny days. Figure 24 shows the irradiance level, where the maxmium vaule was close to 1000 w/m^2. The maximum generated output power reached 1800 W, which is 90% of the rated power of the inverter. The 10% loss is attributed to different types of losses (such as soling, DC and AC losses). As the inverter starts picking up sunlight, the power factor moves close to unity power with a small amount of injected var from the inverter at around 80 var.

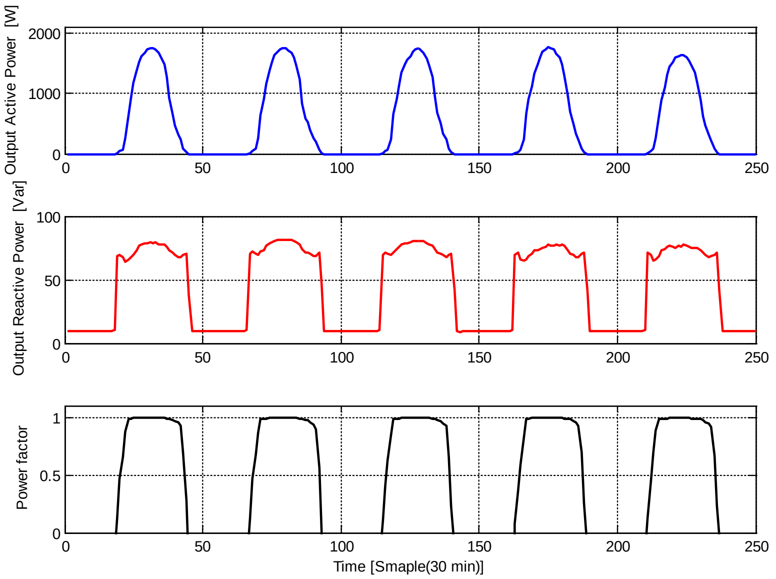


Figure 23 Active power, reactive power and power factor.

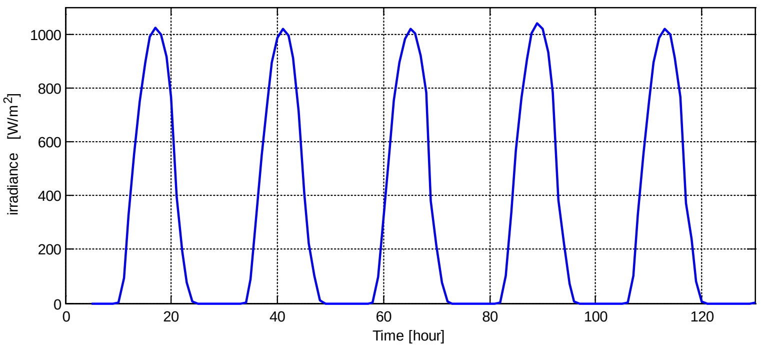


Figure 24 Irradiance level from May 2nd to May 18, 2017.

4 Conclusion

In this paper, the power quality characteristics of a grid-connected inverter for photovoltaics were analyzed. Based on the studied system, it was revealed that the existence of PVs within a low voltage (commercial area) increases the voltage at the connection point up to 6.0%. The THD voltage decreases as the generated power from the inverter increases. The voltage quality is within the acceptable range; however, the current quality is highly correlated with the operating conditions of the inverter, mainly the active power.

Furthermore, during the first test period it was found that the THD_I level started to drop below 20% when the inverter started generating 2.0 Amp (23% of the inverter rating) and started to drop below 10% when the inverter generated more than 3.4 Amp (40% of the inverter rating). The same observations were made during the second test period. During the third test period, the selected day was very cloudy and the THD_I value dropped to less than 10% when the converter started generating more than 50% of the inverter rating. Among the dominant current harmonics order, the 7^{th} and 9^{th} harmonics orders were the main contributors to the THD_I value at both high and low irradiance levels.

It should be noted that the studied system was a small-scale PV system. However, under high proliferation of single-phase PVs, the aforementioned conditions may escalate and cause serious problems related to power quality in low voltage networks. Therefore, future integration of single-phase photovoltaics should be carefully considered.

Acknowledgement

This work was funded by Scientific Research Support Fund (SRSF), Jordan (Grant Number Ene/1/4/2015).

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