Power Quality of Residential PV System under Low Solar Irradiance and Off-Grid Operation

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Abstract — **Recent advances in grid-tied photovoltaic inverters are allowing more flexibility including Volt/VAR control, variable power factor operation, and adjustable ride-through capability. Some new inverters can now operate in stand-alone mode in case of a power outage during the daylight hours. Inverters are also known to supply currents that are highly distorted when operating under low solar irradiance. This paper evaluates how such distortion varies with the power produced by a modern single-phase PV inverter through field measurements. Additionally, the quality of its supply voltage, when operating off-grid, is analyzed in terms of its harmonic content under different loading conditions.**

Index Terms — **Grid-interactive PV inverters, off-grid operation, waveform distortion, harmonic analysis.**

I. Introduction

Global conditions in recent years have led to an expanded appetite for renewable energy sources. The diminishing fossil fuel supply, the political instability of countries producing these fossil fuels, the ever-more destructive effects of global warming, and the lowering of costs for renewable energy technologies have made countries around the world reconsider their sources of energy. The proliferation of PV systems especially has surged recently with the decreasing initial costs for installation [1], and increasing government support in the form of renewable energy portfolios, feed-in-tariffs, tax incentives, etc. [2]. Soon, PV generation may provide for a significant portion of electricity demand [3], even as much as 16% by 2030 [4].

One inherent problem with PV systems, however, is the necessity to convert the PV array's direct current to the electrical grid's alternating current, which is implemented by means of pulse-width modulation (PWM). Such electronic switching introduces more distortion into the grid which already contains some harmonics that are caused by nonlinear loads. As such, electrical standards such as IEEE Std. 519-2014 [5] and IEEE Std. 1547 [6], have been developed to limit these harmonic emissions. Herein, the total distortion, in percent of the PV inverter rated current is limited to 5%. This quantity is sometimes referred to as Total Demand Distortion (or TDD) – a term which was originally introduced for nonlinear loads. But since PV inverters are power generators, a more appropriate term would be "Total Generation Distortion" (TGD) which is used in this article instead of total demand distortion. The above standards also limit the levels on individual harmonics components, exclusive of any harmonic currents due to harmonic voltage distortion present in the area power system prior to connecting the PV system.

Although PV inverters rarely (if ever) operate at their specified power rating, The US interconnection standards do not address harmonic emissions when such systems operate below rated conditions. This curiosity attracted a number of researchers who investigated the harmonic content of the current generated by PV inverters when running at sub-rated power. Reference [7] performed computer simulations and concluded that the current Total Harmonic Distortion (THD) increases dramatically under low power production. Testa et al. [8], [9] conducted thorough laboratory experiments on 3 types of inverters using a PV simulator and a controllable power supply, and quantified harmonic emissions in terms of individual harmonics, Total Harmonic Current (THC) , Total Harmonic Distortion (THD), and Total Demand Distortion (TDD), while field measurements on real PV systems were analyzed in Refs. [10] - [12]. A general conclusion from these studies is that the current THD increases sharply under very low solar irradiance. Furthermore, the harmonic currents generated by PV inverters depend on the quality of the power supply (both in terms of its background harmonic content and source impedance), as well as the type of inverter and its internal controls. In Ref. [13], the authors conducted field tests on a smart PV inverter, and determined that the current harmonic amplitudes (in Ampere) are essentially independent of solar irradiance, nor when activating of some of its advanced functionalities such as non-unity power factor operation and Volt/VAR control. Additionally, the harmonic current components are founded to be affected by the background harmonic components of the voltage supply.

This article continues the work above thought field measurements on a new grid-tied inverter PV inverter that is equipped with a Secure Power Supply (SPS) module which can provide power to critical loads during power outages

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[14]. Such a concept permits a normally grid interactive system to operate as a stand-alone system when disconnected from utility electrical power system, and it is approved by the National Electrical Code (Section 690.61) [15]. Section II analyzes the current distortion when the PV system is operating under low solar irradiance. Section III describes the voltage distortion generated by the same inverter when operating in islanded mode under different load conditions. Finally, the article ends with a conclusion in Section IV.

II. Grid-Tied Operation under Low Solar Irrandiance

The PV system in this study is composed of a 5.94 kW array that consists of 2 parallel strings, each containing 11 panels that are rated at 270 W under STC. The array is connected to the local 208 V grid supply through a single-phase 6 kW transformer-less inverter. The inverter specifications sheet indicates that the harmonic content of the current it generates under rated conditions is less than 4%.

The quality of the utility supply voltage was analyzed by monitoring its trend (with Fluke-3 Model 1735), and taking snapshots of its waveform (with AEMC Model 8220). Both of these instruments can record up to the 50th harmonic order. The supply voltage was found to vary just within ± 0.6% of its average value of 1.02 p.u. over a 24 hr period. Furthermore, its THD varied between 1.3% and 1.8% and averaged only 1.5% over the same monitoring period, and its harmonic content is dominated by the 5th order component. These figures are well below the recommended limits [14] which now allow supply voltages below 1 kV to contain up to 8% THD and each harmonic component is limited to 5%..

To analyze the current harmonic content of the PV inverter at hand under low solar irradiance, the above power analyzers were installed at its terminals to record the trend in power generation and current distortion during the late afternoon hours of a clear day, and capture snapshots of current and voltage waveforms while in operation. Figure 1 below shows the variation in the supply voltage and its harmonic content from 16:50 pm till sunset at 18:14 pm. Figure 2 shows the variation in the power generated by the inverter (in % of rated value of 6 kW), and current THD. Note that as the power generated dropped below 15%, the current THD started to rise at a rapid pace and reached 200% before the inverter stopped power production.

Samples of current and voltage waveforms were also taken at different levels of PV power production. Figures 3(a) and 3(b) show such waveforms when P = 75%, 50%, 25%, 10%, 5% and 1% of the rated value, or 4.5 kW, 3 kW, 1.5 kW, 600 W, 300 W and 60 W, respectively. Since the change in voltage waveform was minimal and hardly noticeable, only one waveform is shown in these Figures. The increase in current waveform distortion with a decrease in power generation is clearly noticeable.

Figure 4 shows the harmonic content, in percent of the fundamental component, of each of the 6 current waveforms displayed in Fig. 3 up to the 19th order. Note that a logarithmic scale is used in the vertical axis since some components are two orders of magnitude larger than others. It is also noted that the 5th harmonic component is most dominant, followed by the 11th, 13th, and 3rd harmonics. The RMS value of the fundamental currents that correspond to these waveforms are respectively equal to 21.6 A, 14.4 A, 7.2 A, 2.9 A, 1.4 A, and 0.3 A, and their THD are displayed in the corner of Fig. 4.

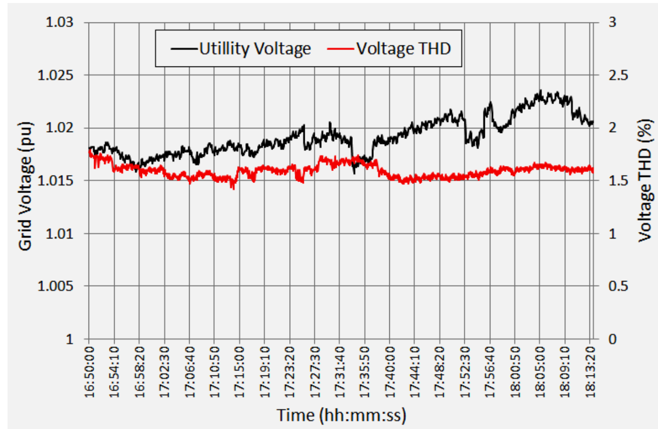


Fig. 1: Trend of RMS value of supply voltage and its THD during recording period.

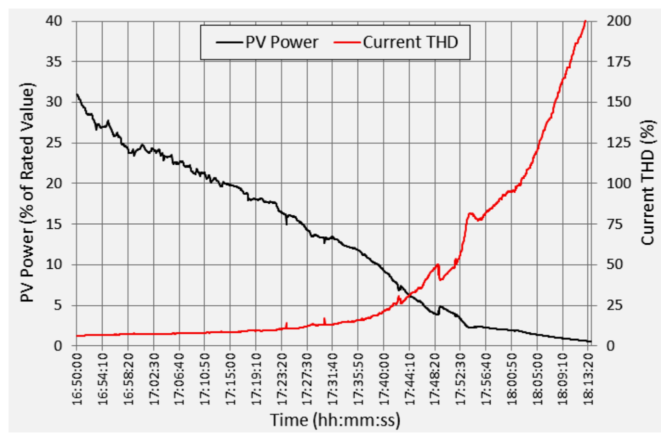
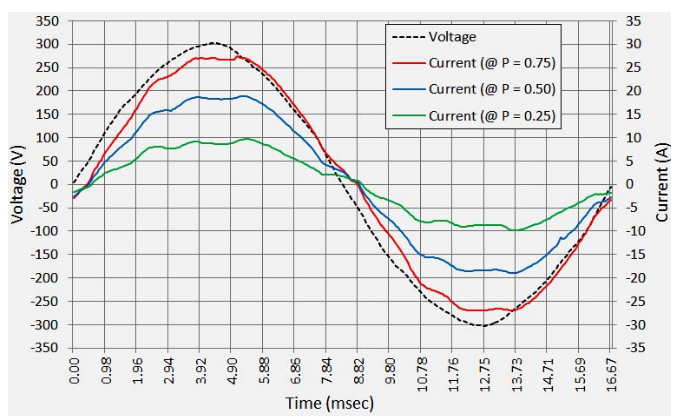
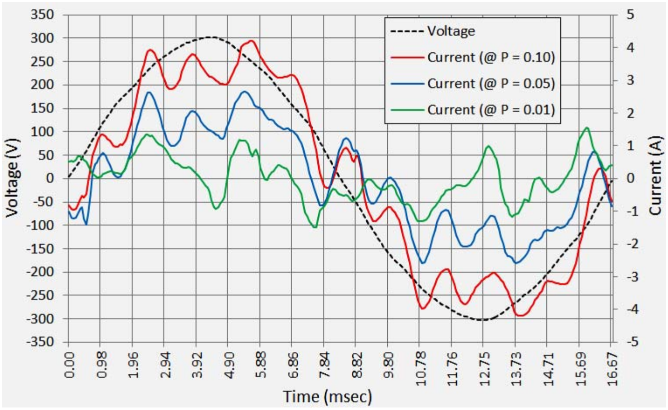


Fig. 2: Trend in PV power and current THD during recording period.



(a)



(b)

Fig. 3: Current and voltage waveforms at different levels of PV power production, (a) P = 75%, 50%, 25%, (b) P = 10%, 5% and 1%.

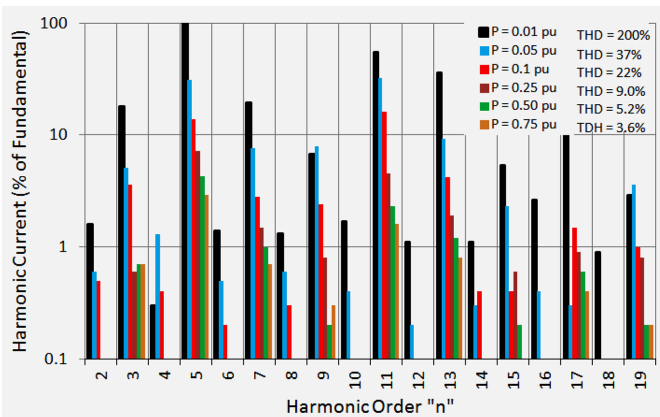


Fig. 4: Harmonic content of current wavefroms (% of fundamental) under different levels PV power production.

Figure 5 shows the actual harmonic content of the 6 current waveforms above in Ampere instead of their magnitudes relative to the fundamental component. While the fundamental component is proportional to power production, there is no clear trend in the variations of the individual harmonic components. But the Total Harmonic Current (THC), i.e., the square-root of the sum of the squares of all harmonics, appears to decrease by a very small amount relative to the decrease in fundamental current, i.e., from 0.71 A to 0.50 A as shown at the top corner of the Figure.

III. Stand-Alone Operation

One of the biggest problems with grid-interactive inverters is that they have to shut off and stop producing power following a disturbance in the power system (e.g., power outage, or events that cause the voltage or frequency to deviate above or below the permitted values). One solution to this is to have a battery back-up power supply to feed critical loads, but this can be costly. For this reason, at least one of the major inverter manufacturers now provides an alternative and cost-effective way to supply power during daytime grid outages through a separate inverter terminal with a 120 V socket-outlet [14]. In this case, the inverter behaves like a voltage source rather than a current source. However, such "secure power supply" operation cannot function simultaneously with grid-tied operation, i.e., the inverter activates the secure power supply terminal only after turning ON a manual switch which disconnects it from the grid. When sufficient sunlight is available, this outlet can be used to run small appliances that can consume up to 2 kW in the inverter under study, that is 1/3rd of its rated power in grid-tied mode. The inverter will automatically attempt to connect to the utility grid only after such a switch is turned OFF.

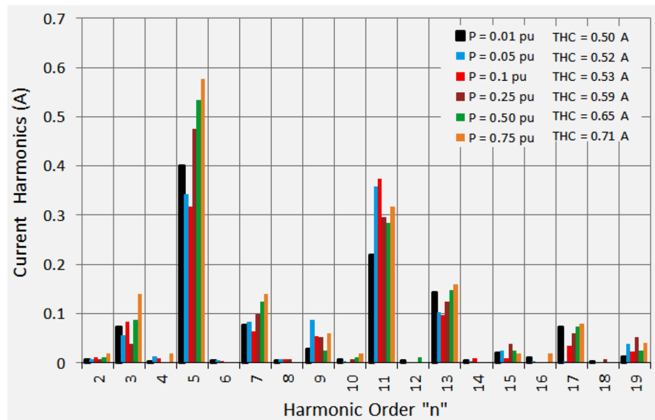
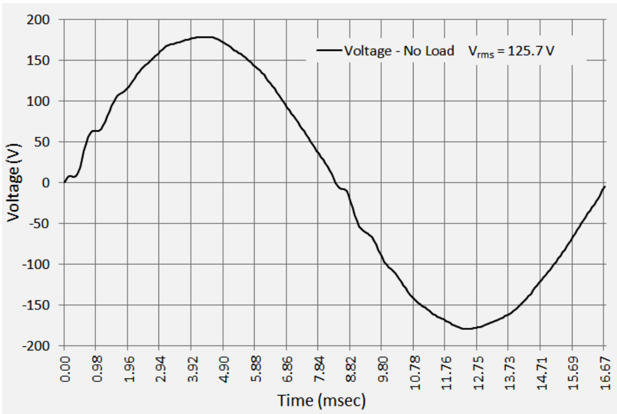


Fig. 5: Harmonic content of current wavefroms (in Amps) under different levels of PV power production.

This section summarizes the quality of the voltage supplied by the inverter (in terms of its harmonic content and variation in RMS value) when operating in stand-alone mode under various load conditions. Initially, the inverter supply voltage was examined under no load, and Figure 6 displays the voltage waveform and its harmonic content up to the 35th order. Note that the RMS value recorded 125.7 V (just below the upper tolerance boundary of 126 V that is defined by ANSI C84.1 Standard), and its THD registered 2.3% which is well within the statutory limit imposed on the grid supply by IEEE Std. 519-2014. The distortion around the zero-crossings can be clearly seen in Fig. 6(a). Another remark is that its harmonic spectrum in Fig. 6(b) resembles a filtered pulse-width-modulated waveform of a full-bridge single-phase inverter that is over-modulated (modulation index > 1) with a carrier frequency at 1.26 kHz (21st harmonic). While an L-C filter reduces the switching frequency related ripple [16], its effectiveness depends on the load impedance. Some electric loads were then connected to the secure power supply to determine how they affect the quality of the voltage supplied by the inverter. These include an air pump, a golf cart batter changer, and a pure resistive load. The resulting voltage and current waveforms and their harmonic contents are described next.

The first load was an air pump which consumed 230 Watts and happened to draw a non-sinusoidal current with a THD of 15.5% as shown in Fig.7 below. This load current contains mainly the 3rd harmonic followed by a noticeable ripple whose frequency is in the 2.5 kHz range (around the 45th harmonic). This particular load resulted in just 1/10th of a Volt drop at fundamental frequency, and "smoothed out" the voltage waveform around its zero-crossings, and reduced all the voltage harmonics, especially the 3rd component which dropped from 0.9% to 0.5%. The resulting voltage THD dropped from 2.3% down to 1.8%.



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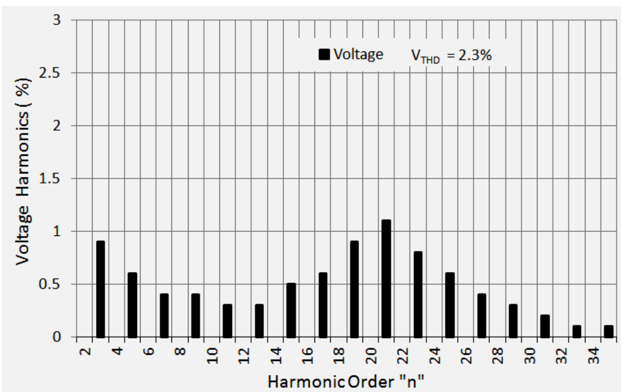
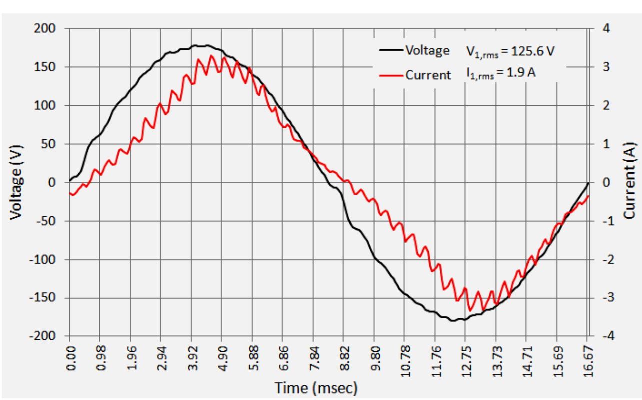


(b)

Fig. 6: Inverter supply voltage under no load, (a) waveform, (b) harmonic content.

The second load was a golf cart battery charger which was consuming 980 W (near 50% of the outlet rating) at the time the measurements were taken. This resulted in a voltage drop of 3.6 V, or 2.9% of the original value under no load. The current THD of this charger is 7.1% and contains primarily low-order harmics with the largest being the 5th, followed by the 7th, 9th, 3rd, and 11th order as depicted in Fig. 7. This led to an increase in voltage harmonics (many of which more than trippled) and led to a rise in voltage THD to 3.7%.



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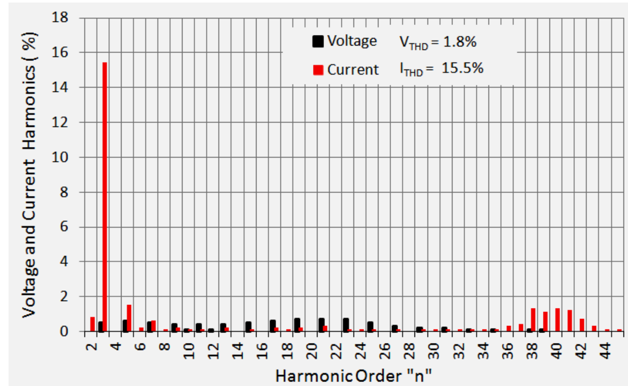
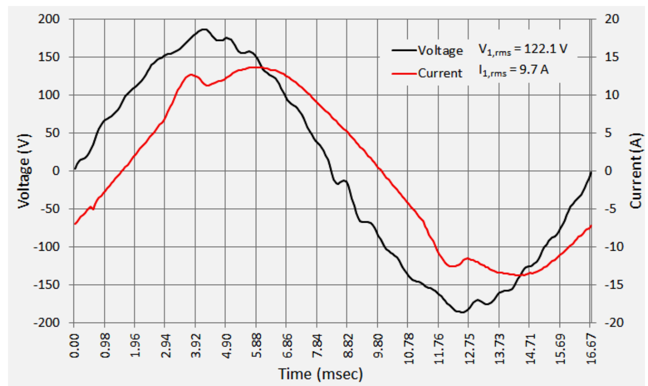
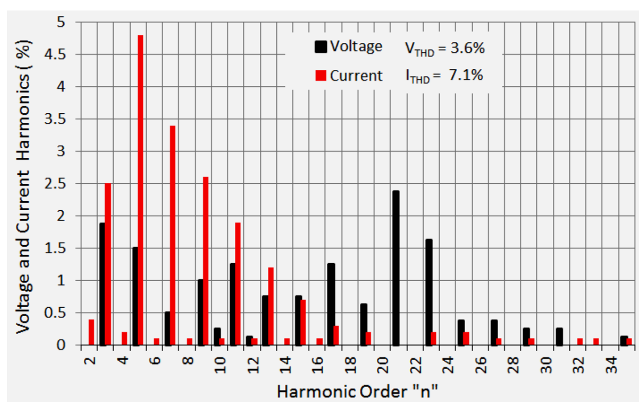


(b)

Fig. 7: Inverter supply voltage and current with 230 W air pump load, (a) wavefroms, (b) harmonic content.



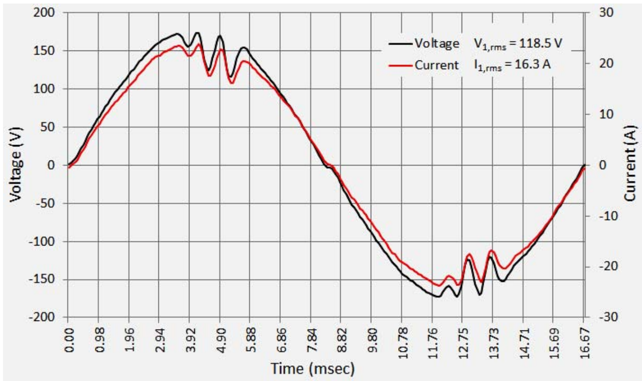
(a)



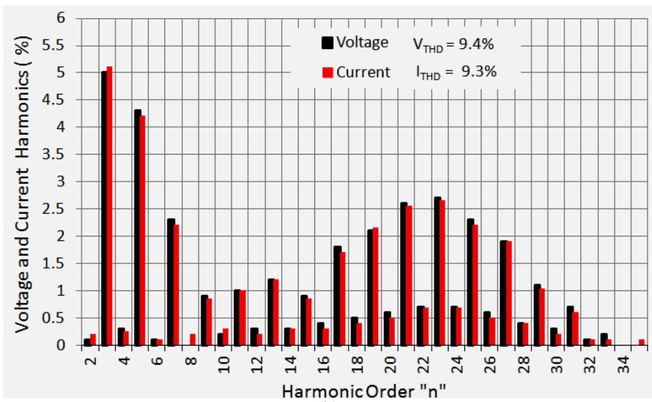
(b)

Fig. 8: Inverter supply voltage and current with 980 W battery charger load, (a) wavefroms, (b) harmonic content.

The third and last load that was connected to the inverter while operating in stand-alone mode was a purely resistive heating element that consumed 1.9 kW (just below the maximum allowed loading). Fig. 9 shows the current and voltage waveforms along with their harmonic contents. Herein, the voltage dropped by nearly 6% from its no-load value, but it is still well within the tolerance boundary, and its THD increased to 9.4% that is 4 times the original value. While each individual harmonic increased, the sharpest rise occurred in the 3rd and 5th orders. In addition, the waveform now contains even harmonics which did not exist prior to load switching.



(a)



(b)

Fig. 9: Inverter supply voltage and current with 1.9 kW resistive load, (a) waveform, (b) harmonic content.

IV. Conclusions

The paper analyzed the harmonic content of the current generated by a single-phase grid-tied inverter when operating under low solar irradiance, and of the voltage it supplies to various loads when operating in off-grid mode under sufficient sunlight. The levels of current distortion are in agreement with those reported in the literature, namely, the THC, and hence the TDD remains fairly constant, while the THD increases dramatically under low power generation due to its inverse relation with the fundamental current. In stand-alone operation, the results show that the inverter supplies a voltage that remains within the tolerance boundary. The amount of voltage distortion depends on the type and size of load being served. The worst recorded voltage THD was with a linear resistive load that was drawing near rated inverter power, and this slightly exceeded the recommended distortion limit of the utility supply.

V. Acknowledgment

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