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Performance and Harmonic Evaluation of a Modified Sinewave 1kVA Solar Powered Inverter

OS Adeoye, AJ Ojo, M Ogunlowo
Department of Electrical and Electronic Engineering, The Federal Polytechnic, Ado-Ekiti, Nigeria

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Abstract: An inverter is a device that takes a direct current input and produces a sinusoidal alternating current output. It maintains a continuous supply of electric power to connected equipment or load by supplying power from a separate source, like battery, when utility power is not available. It is inserted between the source of power and the load is protecting. This paper evaluates and analyses the harmonic characteristics of a 1kVA solar powered inverter under different load conditions. The performance of inverter is affected by the presence of harmonics which is generated from non-linear loads as used in PV systems (i.e inverter) which in turn consequently affects the inverter output voltage and waveform. The methods used comprises of 12V, 250W solar panel connected to a 30A pulse width modulation (PWM) charge controller and a 12V, 100Ah deep cycle battery was connected to the controller to enable charging of the battery while a 1kVA, 220V inverter was connected to the battery to produce the AC output needed. The performance of the inverter was evaluated and analyzed from the load test results and harmonic characteristics occurring in the inverter output voltages and waveforms were obtained using DENT Power meter. The parameters were taken at an interval of minutes and it was observed that the nonlinear loads have more harmonics injection effects on the output waveforms of the inverter. The paper recommends on best practices and further research to identify harmonic constraints in PV inverters, and on the application of mitigation techniques that lead to more PV penetration without sacrificing the safety and reliability of the distribution networks.

1. Introduction

Solar is a proven and significant renewable energy source, offering a more economical way to generate electricity and curb carbon emissions to meet energy and climate goals. If energy companies replaced their most expensive coal plants with new solar power projects or on shore wind farms, totaling 500 GW globally, they could save billions of naira every year and reduce total global carbon emissions by 5%, according to the International Renewable Energy Agency [1]. However, as solar power becomes more prominent, it is important to remember that it is a dynamic system and not immune to challenges. When a photovoltaic (PV) system is connected to the grid, new power quality issues can occur due to the intermittency and instability of solar energy [2]. In an electric power system, a harmonic of a voltage or current waveform is a sinusoidal wave whose frequency is an integer multiple of the fundamental frequency, which needs consideration when using solar energy. The ideal power source for all power systems is smooth sinusoidal waves. However, when waveforms deviate from a sine wave shape, they become harmonics. Inverters that convert the DC current to AC current can also create harmonics [3]. Photovoltaic (PV) systems that is connected to the grid have become a viable option in low-voltage (LV) networks due to the introduction of lucrative policy frameworks such as metering and significant cost reduction in PV system installation [4]–[6]. Consequently, a large amount of solar PV is expected to be connected to utility grids in coming years. A considerable amount of solar PV is already connected to weak grids; this large penetration of solar PV at the LV distribution grid has a significant effect on harmonic pollution levels in the network. Power quality issues related to the low power factor of nonlinear loads and high harmonic current emissions from solar PV inverters at the LV network greatly affect the network performance. The power electronic inverters that do not produce pure sine waves introduce harmonics into the system when connected to the low-voltage grid. From the perspective of power quality, it is desirable that a pure sinusoidal waveform of current is obtained at the output of the grid-connected PV inverter. However, due to the presence of power electronic inverters, harmonics may arise at the output of the inverter and travel through the impedance of the distribution system, resulting in distortion of the sinusoidal voltage waveform of the utility grid. Maximum power point tracking (MPPT), anti-islanding, grid fault conditions, and energy measurement are important characteristics of PV inverter [5]. Usually, residential PV systems have small to medium sizes (1 to 15 kWp) compared to the high short-circuit levels of the distribution grid. Therefore, distortion in system voltage is almost negligible when a single PV system is connected to the grid. However, when multiple connections are made at the same feeder or distribution grid, it may affect the system voltage at the point of common coupling (PCC). For sustainable operation of the power system, harmonic analysis facilitates the integration of grid-connected solar PV into the system. To gauge the harmonic impacts triggered by grid-connected solar PV systems, several studies have been performed over the past few years [6].

Harmonics are also introduced by the presence of non-linear loads and switching devices connected to the grid. Residential non-linear loads generally comprise devices such as transformers, compact fluorescent lamps (CFL), light-emitting diodes (LED), fluorescent tubes, air conditioners, inverters, mobile chargers, switch-mode power supplies (SMPS), television, computers, and laptop chargers. SMPS are commonly present in laptops, computers, and battery chargers for mobile phones. Globally, non-linear loads in residential settings make up 38–42% of the utility loads, while lighting loads vary from 40 to 70%. Non-linear loads, when supplied with sinusoidal voltage sources, produce harmonics in the supply waveform and consequently affect the operation of other linear devices connected to the distribution grid [7].

2. Literature Review

This literature review addresses two main categories, which are the photovoltaic (PV) system (specifically in providing an insight to available inverter designs), related power quality issues and harmonics.

2.1. Harmonic Sources

Harmonics of a waveform are components whose frequencies are multiple integers of a 60 Hz or 50 Hz fundamental wave. For example, 100 Hz, 150 Hz, 200 Hz, and 250 Hz are the 2nd, 3rd, 4th and 5th harmonic components of a 50 Hz fundamental waveform [8]. Harmonic distortion is usually caused by non- linear devices in electric power systems. Harmonics pose a risk to power systems in

Corresponding Author,
E-mail address: adeoyesamuel2012@gmail.com, ojamesalaba93@gmail.com and jide4tees@gmail.com

terms of overheating of transformers, motors, lines, and cables which can lead to shortened life, interference with communication systems (generally for services on the same electric pole such as cable TV and phone) and with the operation of sensitive loads, and outages associated with blown fuses and failed equipment [9]. Power electronic converters, which are widely used in modern power systems, are some of the major sources of harmonics. Solar photovoltaic generation depend extensively upon power electronic converters to produce alternating current output for interconnection purposes. Therefore, the harmonic issue is one the most important aspects affecting the integration of renewable energies [10]. A PV unit is comprised of the PV panels that generate DC, and the inverter, which converts DC to AC. Inverters are power electronic devices that are major sources of harmonics. The harmonic current is injected from the inverters to the distribution circuit potentially affecting customers connected to the same circuit [8].

2.2 Inverter

Inverters are crucial energy conversion components in any renewable energy scheme which converts DC power to AC energy required by most electrical loads. The ideal inverter has hundred percent of efficiency and produces a perfectly sinusoidal output waveform. Production of a perfect sinusoidal output waveform will require the inverter to operate as a linear amplifier which reduces the efficiency figure. To achieve reasonably high efficiency, inverters replace the temporal variations of a sine wave with waveforms that have square edges. Examples of such waveforms include square waves, modified square wave; sinusoidal pulse width modulation (SPWM) synthesized sine wave, and multilevel waveforms [11]. The inverter is one of the most important systems that require attention in harmonic analysis. Due to its switching mechanism causing harmonics in line current, inverters are considered as a contributor to network harmonic voltage distortion [12]. The most common type of inverters used to be the line-commuted inverters, due to the advance in the technology of semiconductor devices self-commutated inverters are blending into PVIs. The basic principle of the inverter is to switch the DC to a required AC voltage. There are a few types of inverter designs with a controllable switching scheme, namely Pulse Width Modulation (PWM) inverters and a special type of PWM called square wave inverter. The square wave inverter harmonic magnitudes can be modeled as ‘1/n’, where ‘n’ is the harmonic number. On the other hand, PWM uses a modulation index scheme and the harmonic components are more complex to derive. In line-commutated inverters the reference frequency is based on the frequency of the supply and they are very sensitive to distortions in the supply [4]. The available literature on inverter designs used in PV systems revealed that there is no specific inverter design or a rating for residential PVIs. This broadness of utilized inverter designs and ratings suggests that the selection of design is at residential preference based on the proposed usage and available space. Therefore, to understand the harmonic content of the output of the commonly accepted inverter designs and ratings, it is necessary to study available literature on practical (large scale) implementations of residential purpose PVIs [3].

2.3 Harmonics in Electrical System

One of the biggest problems in the power quality aspects is the harmonic contents in the electrical system. Harmonics are the distortion of the normal electrical current waveform, generally transmitted by non-linear loads. Example of nonlinear loads- switched mode power supplies; variable speed motors and drives, photocopiers, etc [13]. Electronic harmonic currents generated by nonlinear loads increases heat losses and power bills of end users. These harmonics related losses reduces system efficiency, causes apparatus overheating, and power and air conditioning costs. As the number of harmonics producing loads have increased in the recent year, it has become necessary to address their influence during addition or changes to an installation. Harmonic currents can have significant impact on the electrical distribution system and the facilities they feed. Distortion travels back into the power source and can affect other equipment connected to the same source. Generally harmonics are group under voltage and current harmonics. Current harmonics are usually generated by harmonics contained in voltage supply and depend on the type of load such as resistive load, capacitive load and inductive load. The harmonics can be generated either from the source or load side [14].

3.Methodology

Figures 1-3 show respectively the block diagram, schematic and pictorial representation of the experimental set up for the test and measurements which was carried in the Machines laboratory of the EEE department of the Federal Polytechnic, Ado Ekiti, Nigeria using DENT Power meter. The current, voltage, harmonics spectrums were taken at 5mins interval. Figure 1 Shows the Solar Panel Inverter Block Diagram. Figure 2 shows the schematic diagram of equipment used and the approach of the test.

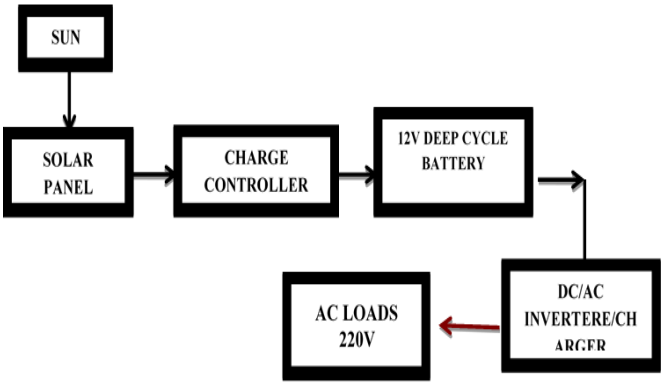

Fig. 1: Solar Panel Inverter Block Diagram

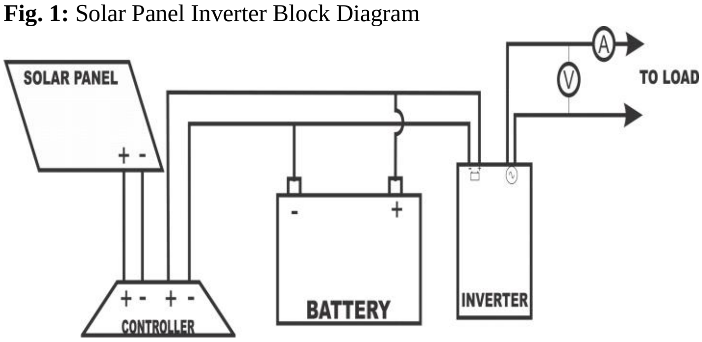

Fig. 2: Schematic diagram of equipment used and the approach of the test

Fig. 3: Experimental set-up for the Research

4. Results and Dsicussion

The solar panel was placed under the sun, the peak sun radiation was on the panel surface and then 33.8volts was observed using a multi meter. While observing the voltage, the panel was slightly adjusted and the voltage varied at an angle away from the sun. The output from the solar panel was connected to the charge controller with respect to their polarities and when the output voltage was observed, it read 12.13 volts which was right for charging 12 volts battery. The voltage was 12 V DC because the solar and the charge controller were connected without load. Then load was added to the inverter which gave an output of 220 volts which was left for about 30 minutes. It was observed again and the voltage did not vary. The inverter has digital read out which display the readings of the inverter. The inverter also had an additional socket for plugging the inverter to mains to serves as another means to charge the batteries other than the solar system. When tested with the volt meter as it was plugged on the mains out, it read 12.08 volts which was basically because of the state of the charge level of the battery. The battery would normally self-discharge over time even when not used. Since the inverter included a triple cycle charger, it could continue to maintain the battery with equalization charge voltage of about 12 volts just to make sure that the battery does not discharge even it was on standby mode.

4.1. Testing of the Inverter under load condition

The duration at which the inverter discharges under load condition depends on the total power of load connected to its output terminal and the power rating of the battery connected to its input terminal. Bearing in mind that total load must not exceed 1kVA.

4.2. Performance Evaluation Test on the Inverter

The 1kVA inverter was subjected to different kinds of loads to determine the efficiency, how long the inverter systems can power the loads. In carrying out the load test, the load shown in table was used. The system was tested to ensure that it meets specification. The test results and performance tests are shown by the table 1.

Table 1: Results of load Performance Test

Time	Load	Load Power Rating (W)	Output Voltage of Inverter (V)	Current (A)	Calculated Power Rating (W)	Battery Voltage (V)
2:26 pm	1 OX standing fan	150w	232	7.2	1,670.4	13.1
2:31 pm	2 OX standing fan	300w	229	16.7	3,824.3	12.8
2:36 pm	3 OX standing fan	450w	220	24.8	5,456	12.2

Table 1, shows the residential loads connected to the inverter output to test the capacity of the inverter based on its designed maximum capacity (1kVA) at different loads and time interval. The output voltage, current and the battery voltage were recorded at different loads and time interval thus, the power rating was calculated at each case as shown in the table above. Load tests were carried out at an interval of five minutes and it was observed that as the load increases ythe output voltage of the inverter decreases from 232V to 220 V. The load current increases with increased loading from 7.2 to 24.8 A while the battery voltage reduces from 13.1 to 12.2 V. It was obvious that the calculated power rating increases with load increment.

4.3.Harmonics Analysis of the 1kVA Solar Powered Inverter

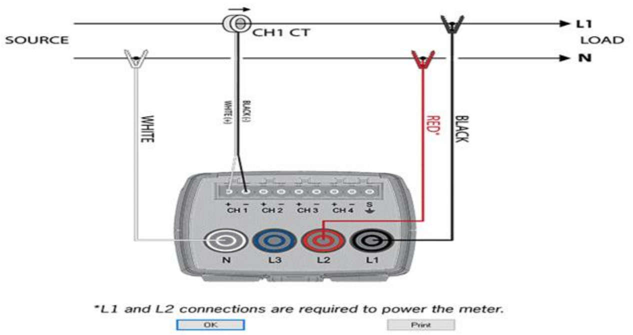

Fig. 4 (a): Typical connection for the DENT Power meter used for the harmonic evaluation

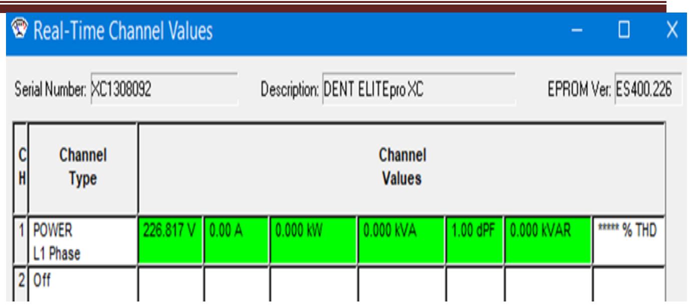

Fig. 4 (b): Parameters of the inverter under no load condition

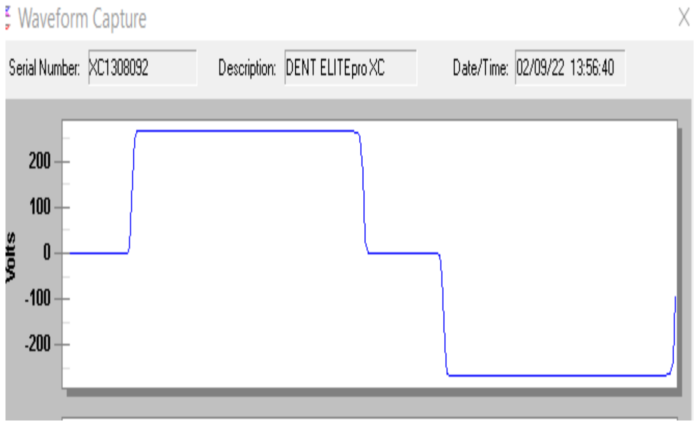

Fig.5: Voltage waveform of the inverter output

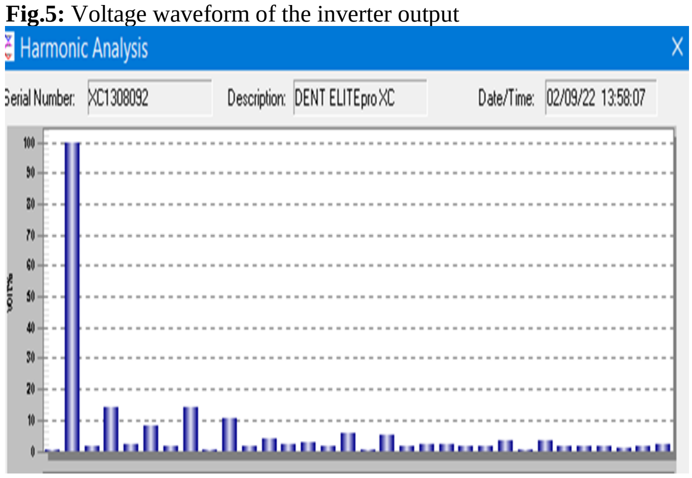

Fig. 6: Voltage Harmonic Spectrum of the inverter output

As shown in figure 4(b), the voltage output of the inverter was 226.82V under no load condition with the Total Harmonic Distortion (THD) giving negligible percentage. Also, figure 5 shows the modified nature of the output voltage with figure 6 showing the voltage harmonic spectrum having between 9 -15% odd individual voltage harmonics with 3rd and 7th harmonics order having the higher values.

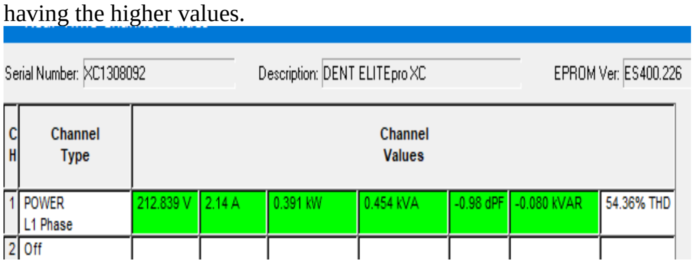

Fig.7 (a): Parameters of the inverter under load case 1

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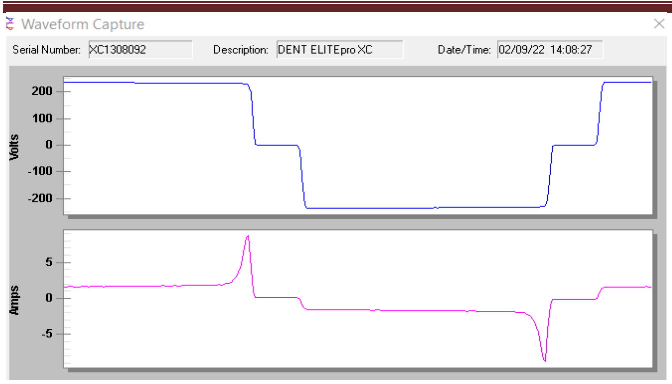

Fig. 7 (b): Voltage and Current Waveforms of the inverter output

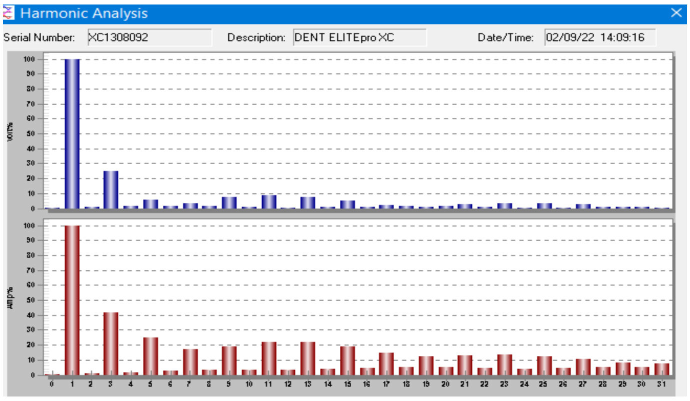

Fig.8: Harmonics Spectrum of Voltage and current output of the Inverter

In this case, 10 numbers of CFLs with each having a rating of 24W were connected to the inverter as load. The total harmonic distortion was 54.36 %. The measured distorted load current was 2.14 A while the output voltage was 212.839 V as shown in figure 7 (a). The output current is distorted due the nature of the load connected to the inverter which has increased the 3rd harmonic distortion of the output voltage which also connotes the high odd harmonics injection by the CFL as shown in figures 7 and 8.

Serial Number: XC1308092 Description: DENT ELITEpro XC EPROM Ver: ES400.226

CH	Channel Type	Channel Values						
1	POWER L1 Phase	208.200 V	2.34 A	0.460 kW	0.486 kVA	-0.99 dPF	-0.053 kVAR	32.24% THD
2	Off							

Fig. 9 (a): Parameters of the inverter under load case 2

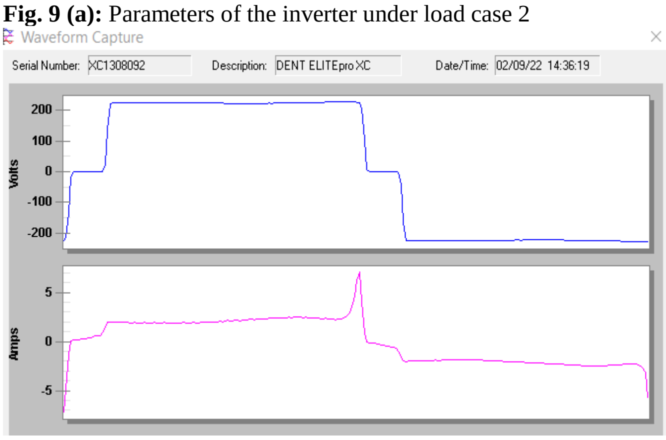

Fig. 9 (b): Voltage and Current Waveforms of the Inverter under load case 2

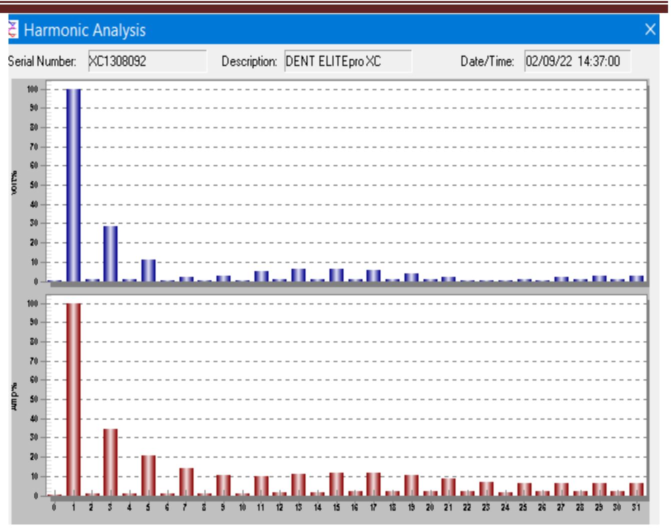

Fig. 10: Harmonics Spectrums of the Voltage and Current of the under load case 2

Serial Number: XC1308092 Description: DENT ELITEpro XC EPROM Ver: ES400.226

CH	Channel Type	Channel Values						
1	POWER L1 Phase	207.363 V	2.49 A	0.498 kW	0.516 kVA	1.00 dPF	-0.035 kVAR	26.10% THD
2	Off							

Fig. 11(a): Parameters of the inverter under load case 3

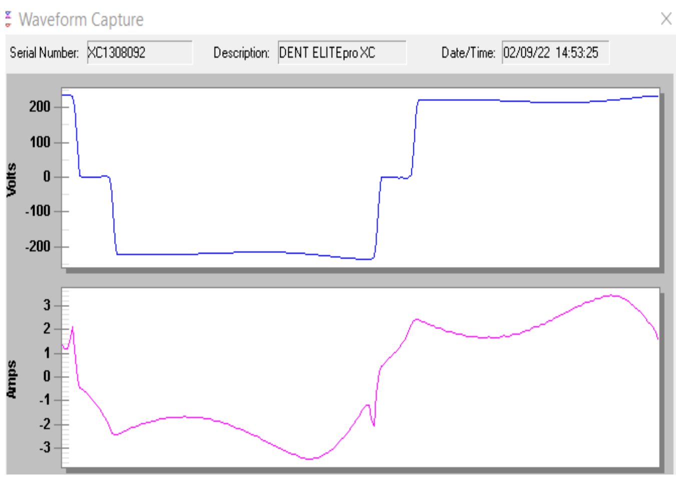

Fig. 11 (b): Voltage and Current Waveforms of the Inverter under load case 3

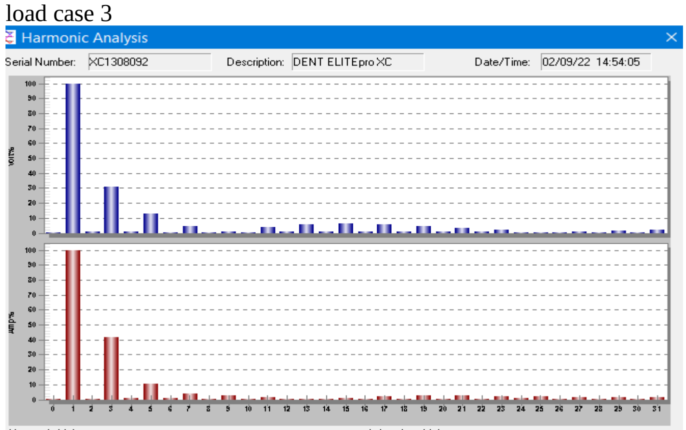

Fig. 12: Voltage and Current Harmonics Spectrum of inverter under load case 3

The second load case involved the combination of CFLs and Ceiling fans as load. The current waveform still shows the distortion due to the inclusion of the CFLs giving a reduced THDs of 32% because of the resistive nature of the ceiling fans. As in case one, the odd order harmonics are still prevalent in both voltage and current waveforms as shown figures 9 and 10.

5. Conclusion and recommendation

This paper presents the performance and harmonic evaluation of a solar power inverter with a modified sinewave output using experimental methods under different load conditions. It is shown from the results obtained that nonlinear loads such CFLs, LED lamps and other linear loads have harmonic injection capabilities on the output of the inverter and in the same vein, the inverter also emits voltage harmonics due to the power electronics components used for the design.

Further research will investigate the various power quality impacts grid connected inverters on distribution systems as integration of inverter technologies penetrations are getting increase on daily basis and to ensure a high quality of the PV plants generated power, power system security and stability, some of the power quality requirements and standards are recommended to be used in coordinating the integration of renewable energy in the distribution networks.

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