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HARMONIC EMISSION OF 1KVA SOLAR - POWERED INVERTER UNDER NO-LOAD AND LOADING CONDITIONS WITH MITIGATION TECHNIQUES

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ABSTRACT

The continuous injections of renewable energies, non-linear loads into the conventional grid networks have increased the emission of harmonic thereby affecting the life span of sensitive equipment. This paper considers the harmonic emission under no load and load conditions and the causes as well as the means of mitigations. The method used was data collection through logging for 24 hours with the aid of data logger called DENT ELITE pro XC. Harmonic emission was measured through experimental procedure on no-load and loaded conditions. The duration of battery discharge was estimated and it ranges from 1.4-2.8 hours with respect to different load conditions with equivalent total harmonic voltage and current being measured as well as load current. The estimated efficiency was 83%. The no-load measurements for output voltage and current are 0 A and 203.305 V respectively. The total harmonic distortion for current and voltage are 0 % and 6.2 % respectively. The first order for current and voltage are 100 A and 100 V respectively while that of third harmonic order are 85 A and 7 V. The fifth harmonic order for current and voltage are 60 A and 3 V respectively. The total harmonic distortion for current and voltage are 110 % and 6.9 % respectively. The mitigation techniques are use of K factor, filters, harmonic elimination by attenuation method such as to attenuate harmonics, passive filters, inductive reactors, phase-shifting transformers, active filters, or multi-pulse converter sections can be used and K-rated transformers. Further research should be carried out in the area of filtering techniques to mitigate the harmonic contents and emission that are dangerous to the life span of sensitive equipment. More harmonic data should be collected in the future by extending the logging time on load condition and artificial neural network could be applied for accuracy.

KEYWORDS: Emission, Harmonic, Injection, Inverter, Mitigation

INTRODUCTION

Harmonic distortion is usually caused by non-linear devices in electric power systems, electric drives and renewable energies. Harmonics of a waveform are components whose frequencies are multiple integers of a 60 Hz or 50 Hz fundamental wave. For example, 120 Hz, 180 Hz, 240 Hz, and 300 Hz are the 2nd, 3rd, 4th and 5th harmonic components of a 60 Hz fundamental waveform (Balcioglu & Soyer, 2017)**.** Renewable sources of energy such as solar, wind, biomass and geothermal attracting many countries as conventional energy sources are depleting. In renewable energy sector, large-scale photovoltaic PV power plant has become one of the important development trends of PV industry (Dartawan et al., 2012). The generation and integration of photovoltaic power plants into the utility grid have shown remarkable growth over the past two decades. Increasing photovoltaic power plants has increased the use of power electronic devices, i.e., DC/AC converters (Dartawan et al., 2012). These power electronic devices are called inverters. Inverters are mainly used to convert direct current into alternating current and act as interface between renewable energy and grid. Inverter-based technologies and various non-linear loads are used in power plants which generate harmonics in system. Intensive efforts have been made to articulate the strategies of eliminating or reducing harmonics distortions generated due to output of this conversion. Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. If the fundamental power frequency is 60 Hz, then the 2nd harmonic is 120 Hz, the 3rd is 180 Hz and so on (Varatharajan et al., 2014). When harmonic frequencies are prevalent, electrical power panels and transformers become mechanically resonant to the magnetic fields generated by higher frequency harmonics. When this happens, the power panel or transformer vibrates and emits a buzzing sound for the different harmonic frequencies. Harmonic frequencies from the 3rd to the 25th are the most common range of frequencies measured in electrical distribution systems (Ahmad & Khan, 2012).The total harmonic distortion (THD) of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental. It provides an indication of the degree to which a voltage or current signal is distorted (Ahsan et al., 2021).Harmonic currents can have a significant impact on electrical distribution systems and the facilities they feed. It is important to consider the impact of harmonics when contemplating additions or changes to a system. In addition, identifying the size and location of non-linear loads should be an important part of any maintenance, troubleshooting and repair program. This paper investigates the causes of harmonics in PV Inverters, effects of harmonics, mitigation techniques (Du et al., 2013).

Harmonic Generation and Effects

Harmonics are voltages and/or currents present in an electrical system at some multiple of the fundamental frequency. Harmonics are any frequency that exists in the system except the fundamental frequency. Harmonics appear as the distortion on the desirable sinusoidal waveform on power line. An inverter is an electronic device that can transform a direct current (DC) into alternating current (AC) at a given voltage and frequency. PV inverters use semiconductor devices to transform the DC power into controlled AC power by using Pulse Width Modulation (PWM) switching (Rahardjo et al., 2021).

Harmonic Current Limit

i. The harmonic current limits specify the maximum amount of harmonic current that the customer can inject into the utility system, i.e., Customer is responsible for maintaining current harmonic components as per acceptable limits (Lulbadda & Hemapala, 2019).
ii. Current limits vary by the ratio of short circuit current at point of common coupling divided by load current (I_{sc}/I_L) (Lulbadda & Hemapala, 2019).

Effect of harmonics

i. Heating Effect: Harmonics current causes heating of equipment’s like power transformers, switchgears, cables, motors, generators etc.
ii. Overvoltage: Harmonic voltage generated by harmonic current flowing against impedance led to significant over voltages which can lead to equipment failure. These over

voltages can be enhanced by system resonance whereby a given harmonic current may generate a large harmonic voltage.

iii. Resonance: when a harmonic current flow in an inductive-capacitive-resistive circuit, it can give rise to series & parallel resonance thereby resulting to a high harmonic current of the appropriate frequency which can produce increased harmonic voltage (Adebayo et al., 2018).

iv. Interference: Harmonics cause interference with communication, signaling, metering control and protection system either by electromagnetic induction or by the flow of ground current. Constructive interference of the harmonics could result into dangerous output voltage or current spike that could adversely affect the load, especially if it is input supply sensitive (Ayaz, 2018).

v. Overstressing and heating of insulation, machine vibration and heating of small auxiliary components of capacitor and motors and malfunctioning of electronics devices.

vi. It also creates possibilities of fuse blowing actions, relay mis-operation and tripping in circuit breakers.

vii. Third harmonic, which causes a sharp increase in the zero-sequence current, and therefore increases the current in the neutral conductor (Osanyinpeju et al., 2018).

Mitigation Techniques

Various harmonic mitigation methods are available and following are some of the techniques:

(i) Harmonic Elimination by Attenuation method: To attenuate harmonics, passive filters, inductive reactors, phase-shifting transformers, active filters, or multi-pulse converter sections can be used and K-rated transformers (Hossain et al., 2012).

(ii) K-Factor determines the total harmonic current which a transformer can withstand without going beyond its specified temperature threshold limits. Under normal circumstances the value of K-Factor ranges from 1-50. It is the load that determines the K-Factor of the specific transformer. For example, in the case of linear loads K-Factor of 1 is used whereas in worst harmonic conditions K-Factor of 50 is advisable. K-Factor rating indicates the tendency of a transformer to supply rated KVA output to a load of specified harmonic content. There are some specific rules set by IEEE which must be followed before choosing a specific K-Factor value for a specific load (Hossain et al., 2012). These include:

(a) For loads with Harmonic currents less than 15% a standard non-K-rated transformer could be used.

(b) For loads with Harmonic currents up to 35%, a K-4 rated transformer should be used.

(c) For loads with Harmonic currents up to 75%, a K-13 rated transformer should be used and for loads with Harmonic currents greater than 75% a K-20 rated transformer should be used.

(iii) Harmonic load at relatively low percentage of total load: In designing or expanding a system, care should be taken that the total harmonic load is kept at a relatively low percentage of the total plant load. If the measured or calculated distortion levels are high, consideration should be given to location of harmonic loads, number of buses, size of the transformers, choice of transformer connections, etc., besides the addition of harmonic filters (Mukherjee et al., 2019).

(iv) Filters: The most common remedial measure for harmonic mitigation is to provide selected harmonic filters tuned to appropriate frequencies. Either existing capacitor banks could be modified to tuned filters by adding tuning reactors, provided the capacitors are adequately rated, or new filter banks could be added (Oommen et al., 2018).

MATERIALS AND METHOD

The method used is the connection of DENT ELITE pro XC which is connected across the supply lines of inverter for twenty-four hours to accurately measure the harmonic emission of the device on no-load and load conditions. The voltages, current and voltage total harmonic distortion were measured. The duration of discharge was estimated based on mathematical model.

RESULTS AND DISCUSSION

Harmonic emission of the inverter was determined by using power quality analyzer and to establish whether or not the tolerance criteria are being met while various tests were conducted at each stage of the execution. Power quality analyzer is an instrument that measures power quality quantities of a device or apparatus. Testing is the act of taking measurement to ascertain whether a product confirms to specified standards and quality. Tests were carried out on the following stages:

i. On No-load
ii. Load condition.

The output voltage of the inverter was a pure sine wave as shown in Figure 2.

They are also referred to as True/pure sine wave inverters. A sine wave inverter waveform smoothly increases to its peak and smoothly increases to its peak and smoothly decreases. They are very costly and are not common in markets. A sine wave inverter has about 3% (THD). These types are reliable, harmless, devoid of interference and similar to the power obtainable from the power outlet. They allow motors to run faster, quieter and cooler. Pure sine wave inverters can safely run more sensitive devices like laser printers, laptop computers, power tools, digital clocks and medical equipment The inverter is less noisy, provides complete automatic switchover function, possess no environmental threats.

Table 1 shows the harmonic behaviour when it is on no-load, therefore, the output current is zero (0) i.e. on no-load and the output voltage is 203.305V. The total harmonic distortion of voltage (THD) = 6.2%. The total harmonic distortion of current = 0%. Table 2 shows the recorded date and the end time of each power line phase to know the THD of the voltage and the current.Fig.3 shows the harmonic distortion of voltage on 1kVA on no-load condition. The fundamental voltage on first order was 100 V, the second order was 3V and the third order was 7V.

On load condition

The effect of the harmonics was also affirmed to be present through testing as the ulterior motive is to produce a sine wave signal. Table 3 shows the total harmonic distortion on load condition. The average voltage was 205. 498 V. Average current was 0.901. The power factor was 1 and the average kVAR for the L1 phase was -0.007. Figure 4 shows the captured waveform for voltage and current of 1kVA inverter on Dent Elite pro XC which indicated harmonic emissions can have varied amplitudes and frequencies. The most common harmonics in power systems are sinusoidal components of a periodic waveform, which have frequencies that can be resolved into some multiples of the fundamental frequency, this shows how the harmonics behave in an inverter of sinusoidal wave.

Figure 5 is the harmonic order for voltage and current. The first harmonic order for voltage and current are 100V and 100A respectively. The third harmonic order for voltage and current are 7V and 85A respectively. The fifth harmonic order for voltage and current are 3V and 60A. Voltage THD =6.9% Current THD = 110%. This shows that this graph is typically of a six-pulse current source converter, harmonics limited to 4th harmonic, though higher harmonics will be present. The harmonic emission varies over wide range of distorted waveform.

Testing the inverter under load condition

The duration at which the inverter discharges under load condition depends on the total power of the load connected to its output terminal and the power rating of the battery at its input terminal. Bearing in mind that total load must not exceed 1000W based on capacity of the design. This test was done to ascertain the fact that the battery bank is able to supply the required load for five hours.

The discharge duration is:

Battery power rating = 12 V and 100 Ampere hour

i. When load (capacitive and resistive) = 550W

$$Duration\ of\ discharge = \frac{\text{voltage rating of the battery} \times \text{Ampere hour of the battery}}{\text{Capacity of load}} \tag{1}$$

$$Duration\ of\ discharge = \frac{12 \times 100}{550} = 2.2hrs$$

Load Current; I = 23A

Voltage harmonics =7.95%

Current harmonics =55 to 65%

The inverter performs when the load is at 550W of 1kVA inverter. The harmonic voltage and the current were at 7.95% and 55-65% which tell us that the inverter is still capable of carrying more load. The duration of discharge, load current, voltage harmonic and current harmonic are 2.2 hours, 23A, 7.95% and 0.55-0.65 respectively.

ii. When load (inductive) = 450W

$$Duration\ of\ discharge = \frac{\text{voltage rating of the battery} \times \text{Ampere hour of the battery}}{\text{Capacity of load}} \tag{2}$$

$$Duration = \frac{12 \times 100}{450} = 2.7hrs$$

Load Current; I = 18.8A

THD voltage = 7.9%

THD current = 17%The duration of discharge, load current, THD voltage and current are 2.7 hr, 18.8 A, 7.9% and 17 % respectively.

iii. When Load (capacitive, resistive and inductive) =810 W

$$Duration\ of\ discharge = \frac{\text{voltage rating of the battery} \times \text{Ampere hour of the battery}}{\text{Capacity of load}} \tag{3}$$

$$Duration = \frac{12 \times 100}{810} = 1.5hrs$$

Load Current; I = 42A

THD voltage=8.3%

THD current = 68%

The duration of discharge, load current, THD voltage and THD current are 90minutes, 42 A, 8.3 % and 68 % respectively. The results obtained during the load on the inverter depend on the duration at which the inverter discharges under load condition and the total power of the load connected to its output terminal. Table 4 shows the equipment used for experimental purposes. Furthermore, the equipment was combined using power laboratory to obtain different wattages as shown in Table 5. The time interval between the start of the equipment up to the time at which the battery voltage drops to 11.3V was computed and recorded. The results of the testing are given in Table 6 with the load wattage and their corresponding time duration and the battery current in ampere before the battery voltage drop to the 11.3V. Table 5 shows the various loads and the time duration. For a 550 W, the battery voltage was 12.6 V, the load current was 23.6 A while the duration was 2.24 hours. For a 450 W, the battery voltage was 12.3 V, the load current was18.1 A and the duration was 3.36 hours. In a similar manner, for a 810 W load, the battery voltage was 12.1, the load current was 42.5 A, the battery voltage was 12.1 V and the load current was 8.24 V. Table 5 shows the duration at which the inverter discharges under load condition depends on the total power of the load connected to its output terminal and the power rating of the battery at its input terminal.

Inverter efficiency

Inverter efficiency testing was conducted over a range of operating voltages and power levels. The inverter efficiency was tested when a load of 300W. The output and input power at the instant of testing was computed using the relation below: The estimated efficiency of the 1 kVA inverter from equation 4 was 83 %.

$$Efficiency = \frac{Power\ Output}{Power\ Input} \times 100\% \quad (4)$$

$$= \frac{1000W}{1200W} \times 100\% = 83\%$$

The efficiency of the inverter refers to the amount of AC output power, it provides from a given DC input, this normally falls between 80 and 95 %.

CONCLUSIONS AND RECOMMENDATIONS

The paper evaluated harmonic emission of 1kVA inverter under no-load and loading condition which was carried .out, and inputs were based on the following factors: economy, availability of research materials, efficiency, compatibility portability and durability. The total harmonic distortion for voltage and current was 6.9 % and 110 % respectively on load condition while the total harmonic distortion for voltage and current on no-load condition was 6.2 % and 0 % respectively. The estimated inverter efficiency was 83 %. The paper concluded that the duration of discharge varied with the load capacity, load current, voltage harmonics and current harmonics.

The following recommendations are necessary so as to achieve a high output and efficient inverter:

i. Research should also be done on building very large capacities of inverters like 2kVA and above with longer length of time of operation at full rated load.

ii. Further research should be carried out on the mitigation techniques of emitted harmonics on inverters.

iii. Extensive review should be carried out using new techniques in carrying out this type of research.

iv. For better accuracy in the determination of harmonic emission, the logging time should be increased to about 720 hours and artificial neural network will be perfect to solving the problems.

REFERENCES

Adebayo, O. E., & Eniola, O. (2018). Design of 2kVA Solar Inverter. *Scientific Research Journal,6*(1), 84–90.

Ahmad, M., & Khan, B. H. (2012). Design and Evaluation of Solar Inverter for Different Power Factor Loads. *Energy and Power Engineering, 4*(5), 324 - 329.

Ahsan, S. M., Khan, H. A., Hussain, A., Tariq, S., & Zaffar, N. A. (2021). Harmonic analysis of grid-connected solar PV systems with nonlinear household loads in low-voltage distribution networks. *Sustainability*, *13*(7), 1 – 23.

Ayaz, A. (2018). *Design methodology of off-grid pv solar powered system (A case study of solar powered bus* *shelter)*. Retrieved from https://www.eiu.edu ->Design%20Methodology%20of%20OffGrid%20PV%20Solar%20Powered%20System_5_1_2018.pdf

Balcioglu, H., El-Shimy, M., & Soyer, K. (2017). Renewable energy– Background. In M. El-Shimy (Ed.), *Economics of variable renewable sources for electric power production*. Germany: Lambert Academic Publishing/Omniscriptum Gmbh & Company kg.

Dartawan, K., Hui, L., Austria, R., & Suehiro, M. (2012). Harmonics issues that limit solar photovoltaic generation on distribution circuits. *World Renewable Energy Forum, Denver, USA*. 1 -7.

Du, Y., Lu, D. D. C., James, G., & Cornforth, D. J. (2013). Modeling and analysis of current harmonic distortion from grid connected PV inverters under different operating conditions. *Solar Energy, 94*, 182 - 194.

Lulbadda, K. T., & Hemapala, K. T. M. U. (2019). The additional functions of smart inverters. *AIMS Energy*, *7*(6), 971 - 988.

Mukherjee, S., Mazumder, S., Sharma, S., Sarkar, T., Dey, S., & Adhikary, S. (2019). Performance of Grid-Connected Inverter Fed from PV Array. *UEMGREEN 2019 - 1st International Conference on Ubiquitous Energy Management for Green Environment. Kolkata, India*, 1 – 5.

Hossain, M. N., Routh, T. K., Yousuf, A. B., Asasduzzaman, M. M., Hossain, M. I., & Husnaeen, U. (2012). Design and development of a grid tied solar inverter. *2012 International Conference on Informatics, Electronics and Vision, ICIEV 2012*,1054 - 1058.

Oommen, T., Sah, G. K., Eshwar, K., Shukla, D. N., Gorat, P., & Meena, P. (2018). Development of a Single-Phase Inverter for Application in a Hybrid Solar UPS. *Proceedings of 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems*, *PEDES 2018*. 1 – 5.

Osanyinpeju, K., Aderinlewo, A. A., Adetunji, O. R., Ajisegiri, E. S. A. (2018.). Performance evaluation of mono-crystalline photovoltaic panels in FUNAAB, Alabata, Ogun state, Nigeria weather condition. *International Journal of Innovations in Engineering Research and Technology*, *5*(2), 8 - 20.

Rahardjo, I. A., Djaohar, M., Subekti, M., & Kamaruddin, E. (2021). Harmonic mitigation in a single-phase inverter. *IOP Conference Series: Materials Science and Engineering,1098*(4), 1 - 5.

Varatharajan, A., Schoettke, S., Meyer, J., & Abart, A. (2014). Harmonic emission of large PV installations case study of a 1 MW solar campus. *Renewable Energy and Power Quality Journal, 1*(12),701 - 706.

Table 1: Percentage Total Harmonic Distortion on no-load condition

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

CH	Channel Type	Channel Values						
1	POWER L1 Phase	203.305 V	0.00 A	0.000 kW	0.000 kVA	1.00 dPF	0.000 kVAR	***** % THD
2	Off							
3	Off							
4	Off							

Table 2: Total Harmonic Distortion Measured by DENT Elite proXc on no load condition

XC1308092-01_GRP_2_NO_LOAD_1

	Record Date	Record End Time	Power 1 Avg. Volt L1 Phase	Power 1 Avg. Amp L1 Phase	Power 1 KW Hours L1 Phase	Power 1 Avg. KW L1 Phase	Power 1 Avg. KVA L1 Phase	Power 1 Avg. PF L1 Phase	Power 1 Avg. KVAR L1 Phase
1	09/02/22	10:40:00	204.402	0.005	0.000	0.001	0.001	1.00	0.000
2	09/02/22	10:45:00	204.096	0.000	0.000	0.000	0.000	1.00	0.000

Table 3: Total Harmonic Distortion measured by DENT Elite proXc on load condition

	Record Date	Record End Time	Power 1 Avg. Volt L1 Phase	Power 1 Avg. Amp L1 Phase	Power 1 KW Hours L1 Phase	Power 1 Avg. KW L1 Phase	Power 1 Avg. KVA L1 Phase	Power 1 Avg. PF L1 Phase	Power 1 Avg. KVAR L1 Phase
1	09/02/22	10:55:00	205.498	0.901	0.010	0.119	0.185	1.00	-0.007

Table 4: Equipment's (Loads in Watts) used for testing the 1kVA solar inverter for resistive, capacitive and inductive load.

S/N	Equipment Loads Specification	Equipment power rating (watt)
1	Twenty AKT bulb 26W each	520W
2	Three (3) Ox fans 150W	450W
3	Eight Ceiling fan 65W each	520W

Table 5: Loads and time duration for different load combinations

S/N	Equipment combinations	Loads (in watts)	Battery-voltage (in volts)	Time duration (in hours)	Load current (in amps)
1	20 AKT bulbs (20W each)	520	12.6	2.24	23.6
2	3 ox fans (150W each)	450	12.3	3.36	18.1
3	20bulbs and 4ceilling fan	780	12.1	8.24	42.5

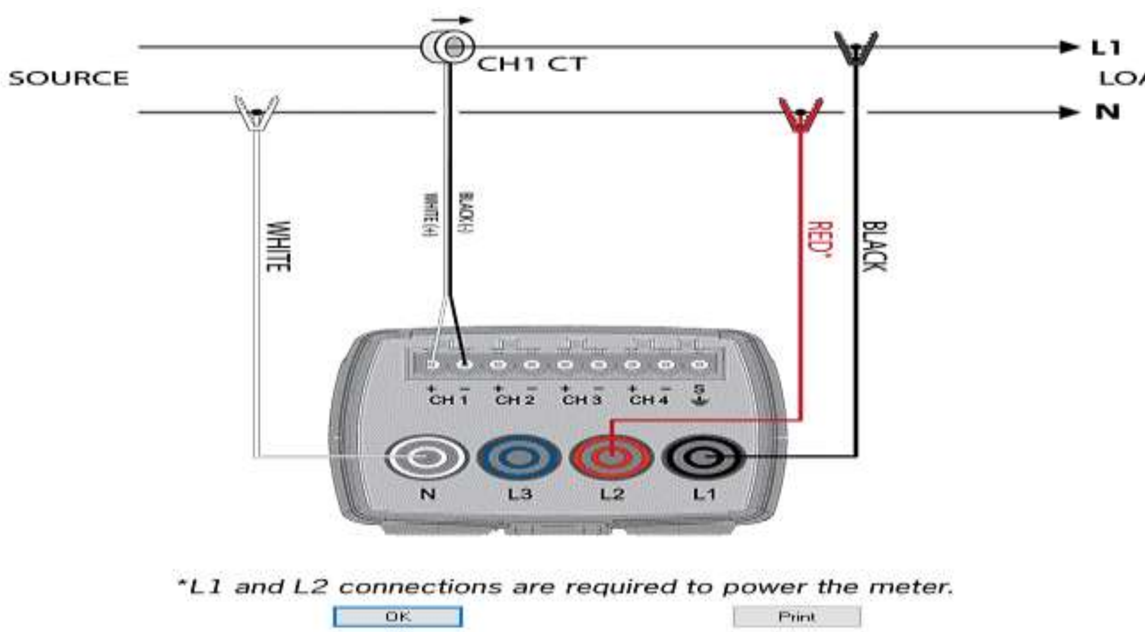

Figure 1. Powering of the Meter (The supply parameters when the inverter is not yet connected (recording instrument).

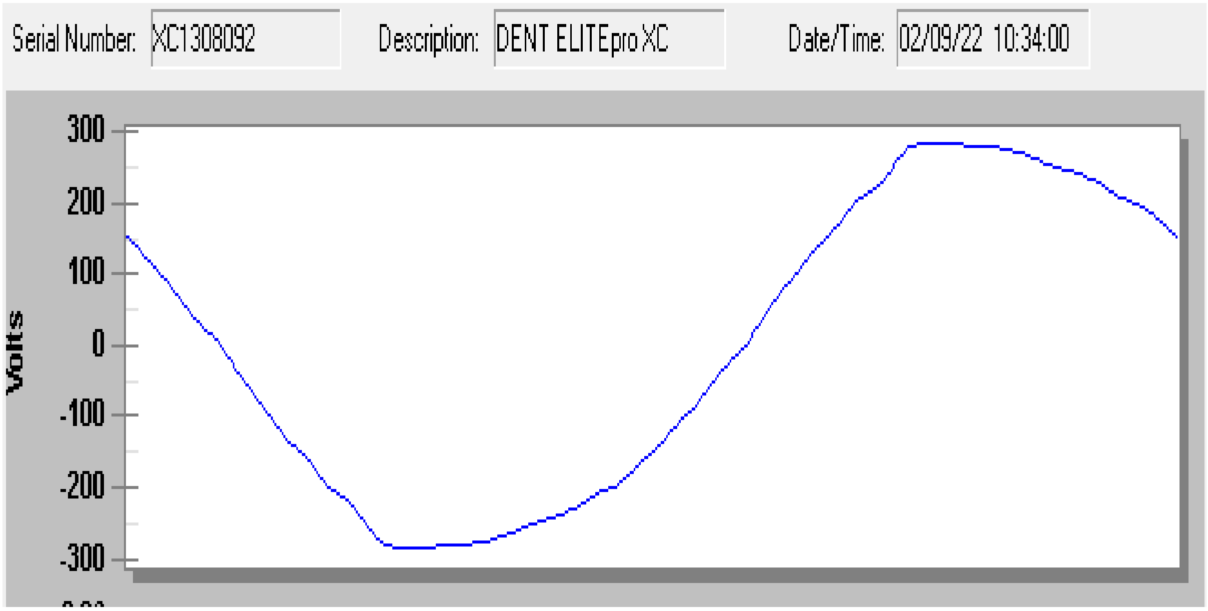

Figure 2. Purely Sine Wave of the Inverter.

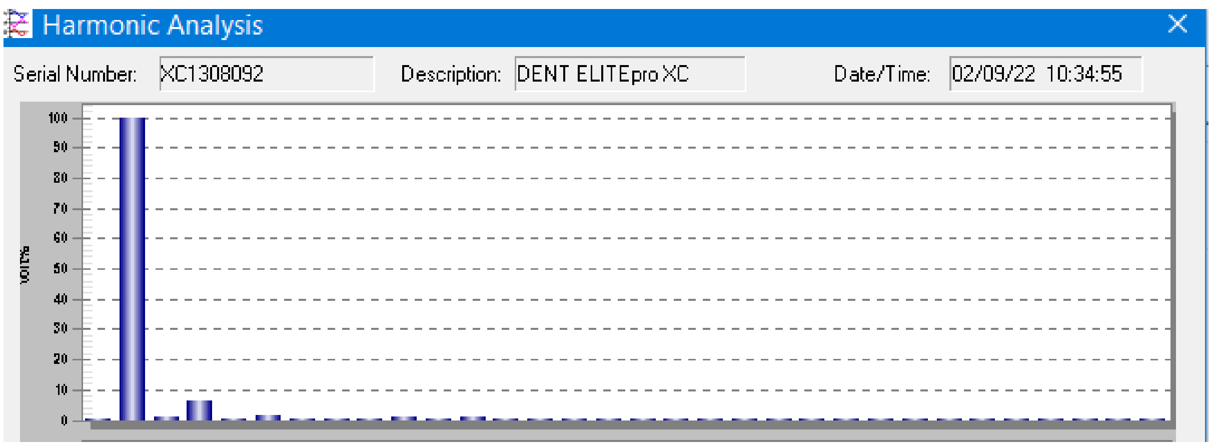

Figure 3. Harmonic Distortion of Voltage on 1kVA on no-load condition

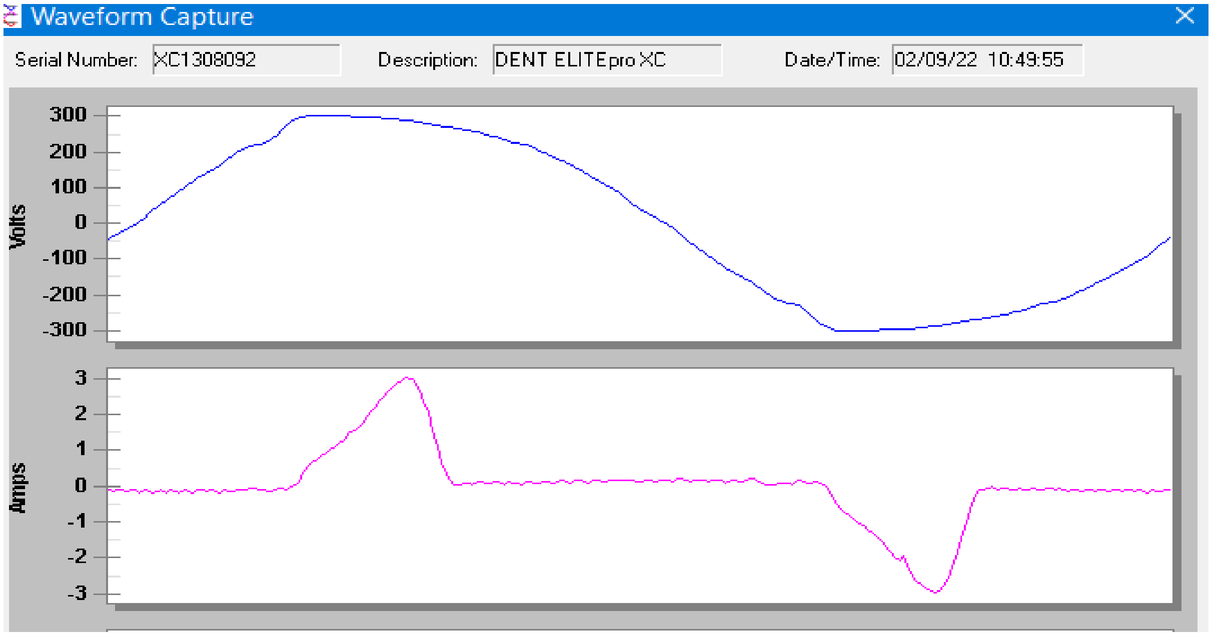

Figure 4. Captured wave form for voltage and current of 1kVA inverter on DENT Elite pro XC

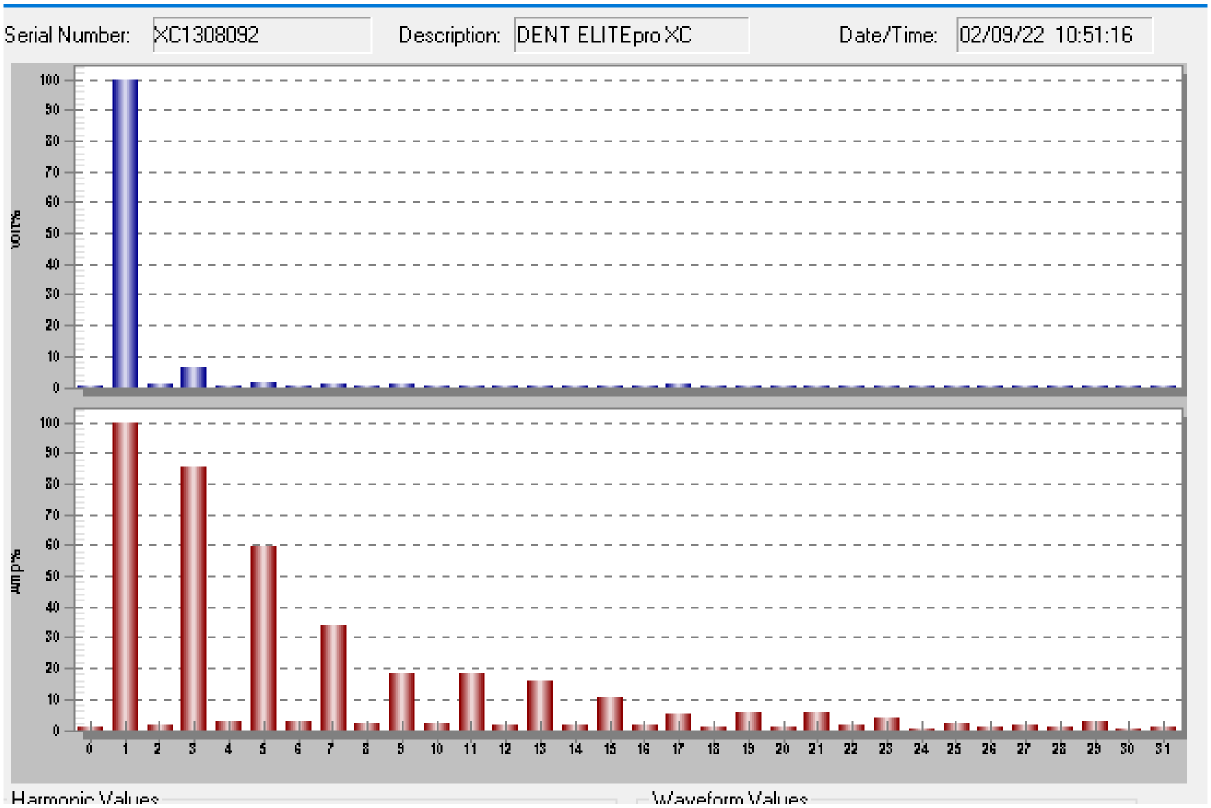

Figure 5. Harmonic order for voltage and current