Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Analysis of Harmonic Contamination at the Output of a 3kVA Hybrid Inverter

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This study examines harmonic pollution in the output of a 3kVA hybrid inverter, identifying the main sources of distortion and proposing solutions to mitigate its effects on the power system. The objective is to evaluate the power quality and propose improvements for optimal and reliable operation. The importance of controlling and reducing harmonic pollution to maintain the efficiency and reliability of the inverter and connected devices is emphasized. The research combines a theoretical and experimental approach with quantitative analysis and simulations, employing the methods of "Wave Recording" and passive filters. The results identified the sources of harmonic distortion under different load conditions, evaluated their impact on system efficiency and analyzed effective solutions, such as the use of tuned filters to minimize losses by 5 % to 6 % and the implementation of "Balanced Load" according to IEE Std 519.
Keywords: P Harmonic Pollution; Hybrid Inverter; Power Quality; Passive Filter.

1. Introduction

Human development has historically been determined by the use of various forms of energy. Initially, renewable energies such as biomass, wind, water and sun were essential. However, the appearance of fossil energy resources made the use of energy more polluting, reaching today an unsustainable consumption. The overuse of this source has prompted countries to improve energy efficiency and reduce the use of fossil fuels. In this context, solar PV stands out as a clean and reliable form of small- and large-scale electrical power production.(Bose, 2013)

In the modern era, hybrid inverters, which combine renewable energy sources with grid and storage systems, have become crucial. Despite their benefits, these devices combined with the presence of non-linear loads, introduce the challenge of harmonic contamination, which is the distortion of the current or voltage waveform due to the presence of harmonics. These harmonics, which are multiples of the fundamental frequency, can cause problems such as loss of efficiency, overheating of transformers, electromagnetic interference, and reduced equipment life.(Kjaer, Pederson, & Blaabjerg, 2005)(Enslin & Heskes, 2004)

The analysis of harmonic pollution is essential to understand its impact on power quality and implement corrective measures. To this end, several researchers such as , in their study "Active Harmonic Filters for Power Quality Improvement", introduced active harmonic filters (AHF), which use electronic components to inject compensating currents and cancel out unwanted harmonics. This technique offers greater flexibility and adaptability compared to passive filters. In the research, high-frequency PWM modulation techniques to reduce harmonics in inverters through precise semiconductor control are highlighted. In 2012, they investigated the impact of harmonics on grid-connected photovoltaic systems, proposing analyses and strategies to improve power quality. Other authors emphasized advanced modeling and simulation techniques to analyze harmonics in hybrid inverter systems, improving the design of mitigation strategies. With this background we can then say that the incorporation of filters and the management of the different loads of the electrical system can reduce the harmful effects of wave deformation in the network as a result of harmonics. (Akagi, 1998) (Holtz, 2004)(Bollen & Hassan, 2012)(Zhang, Wang, & Li, 2023)

Hybrid inverters during their operation can generate harmonics that contaminate the output signal, which can cause problems in equipment connected to the power grid (Bose, 2013), they combine the topologies of voltage source inverters (VSI) and current source inverters (CSI) to take advantage of both, . CSIs, on the other hand, offer better output waveform quality and better current control, beneficial for applications that require high current quality and low harmonic content. This combination and configuration as shown in the (Rodriguez, Jih-Sheng Lai, & Zheng Peng, 2002) (Wu, 2006)(Kazmierkowski & Malesani, 1998)Figure 1 It allows a hybrid inverter to offer fast dynamic response and high output quality, being suitable for high-power applications and power distribution systems.(Khwan-on, de Lillo, Empringham, Wheeler, & Gerada, 2012) (Hart, 2001)

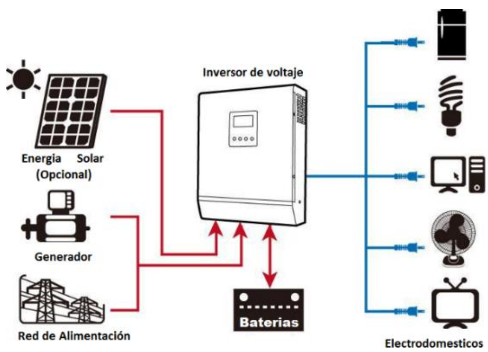

Figure 1 - Diagram of the operation of a hybrid inverter. In original language English

Source: https://himelco.cl/inversor-de-voltaje/inversor-hibrido/

The design and control of hybrid inverters such as the Figure 1 They can be more complex compared to conventional inverters, as they require specific control strategies to coordinate the operation of both topologies. (Rivera, Wu, Kouro, Zhang, & Xu, 2017)

The studies analyzed represent milestones in the evolution of harmonic mitigation and the improvement of power quality in inverter systems, many of these studies were carried out in compliance with international regulations such as IEEE std 519-2014 and CONELEC and ARCONEL regulations in Ecuador. Through a theoretical and experimental approach, complemented by quantitative analysis and computational simulation, it seeks to deeply understand these phenomena and contribute to the development of cleaner and more efficient energy systems

Therefore, the purpose of this research is to examine the harmonics generated in a photovoltaic network with a 3 kVA hybrid inverter, to evaluate the power quality and analyze solutions that minimize and control the harmonic contamination present.

2. Materials and Methods

Harmonic contamination is a common problem in modern electrical systems, caused by nonlinear loads such as variable speed drives, power converters, and electronic devices in switch mode, . (Arrillaga, Watson, & Chen, 2000)(Emanuel, 2010)

In hybrid inverters, it is vital to employ specific harmonic analysis and mitigation methods. These harmonics can lead to efficiency losses and reduce the lifespan of network-connected devices. To address this challenge, analysis and mitigation strategies must be implemented, such as accurate measurements to be able to identify harmonic sources and amplitudes. (Kjaer, Pederson, & Blaabjerg, 2005) (Arrillaga, Watson, & Chen, 2000)(Wakileh, 2001)(Grady & Santoso, 2001)

In Ecuador, the regulation of the quality of electrical power is established by the Agency for the Regulation and Control of Electricity and Non-Renewable Natural Resources (ARCERNNR) which conforms to the IEEE 519 standard, here guidelines are provided for the control and mitigation of harmonics, .(ARCERNNR, 2020)(IEEE, 2014)

Therefore, studies on harmonic pollution in PV systems and hybrid inverters are essential to assess their compliance with standards and propose mitigation strategies. To analyze harmonic contamination in the output of a hybrid inverter, several methodologies have been reviewed in the literature that are indicated below:(Grady & Santoso, 2001)

- Spectral Analysis: It uses Fourier analysis techniques to break down the signal and determine the harmonic components present, as described in J. Zhang's study.(Zhang, Wang, & Li, 2023)
- Mathematical Modeling: Develops mathematical models of the inverter and its behavior under different loads to predict harmonic generation, as in the investigation of .(Gomez & Smith, 2018)
- Software Simulation: It uses simulation tools such as MATLAB/Simulink or PSpice to model inverter behavior and assess harmonic contamination, as proposed in .(Wang, y otros, 2015)

- Experimental Measurement: It performs direct measurements in the laboratory or in the field to obtain real data on harmonic contamination generated by the inverter and/or loads, being fundamental in many practical studies and investigations.(Sharma, Soni, & Bhattacharya, 2018)
- Active or Passive Filtering: It implements active or passive filters to mitigate harmonics and evaluates their effectiveness through measurements or simulations, a widely studied and applied topic.(Fernández, 2019)

2.1. Equipment specifications and procedures used

In the experimentation, a photovoltaic system has been used with a hybrid inverter that has the specifications given in Table 1.

Board 1 - Summary of data from the manufacturer of the Hybrid Inverter used

Model:	InfiniSolar V-LV-3K-24
Characteristics:	Infini Solar V-LV-3K-24 3000VA/2400W Hybrid Inverter, Pure sine wave solar inverter, Output: 120 VAC, 50/60 Hz, Battery voltage 24 V, MPPT. Range 30 - 115vdc, Maximum photovoltaic input power 2000W, Maximum solar charging current 80 A, W/O Parallel funtion up to 6 units, USB, RS232+dry contact. Procet Scientific

Source: The Authors (Inverter Plate Data)

The data and characteristics summarized in the Board 1. These are the parameters that will be used to evaluate the energy efficiency of the inverter. For this study, the MECATRONIK power quality analyzer of the AN1F3F 1120-0122-011 series has been used, which has a voltage range of 80 V to 250 V in alternating current, this analyzer has the advantage that it allows the visualization of the wave deformation in real time.

2.2. "Wave Recording" Method

The Wave Recording method is a technique used to capture and analyze the voltage and current waveforms in an electrical system in order to identify and quantify the harmonics present. In this study, the following sequence has been followed to evaluate harmonics:(Arrillaga, Watson, & Chen, 2000)

- Measuring equipment configuration: Parameters such as sample rate, capture duration and trigger levels are adjusted.

- Data Capture: Voltage and current waveforms are recorded simultaneously as those of the Figure 2:

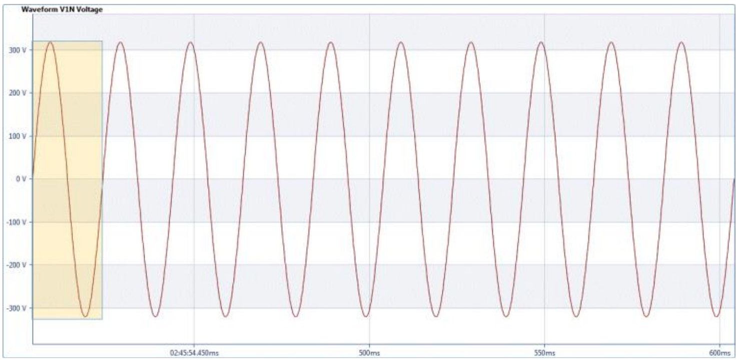

Figure 2 - Shape recording for harmonic recording. In original language English

Source: https://www.elspec-ltd.com/conociendo-la-norma-iec-61000-4-30-clase-a/?lang=es

- Calculation of distortion indices: Parameters such as Total Harmonic Distortion (THD) are determined.

This method involves the use of power quality analyzers and oscilloscopes, which can record waveforms in real-time.

2.3. General Harmonic Contamination

Harmonics are frequency components present in a periodic signal, being integer multiples of the fundamental frequency. The addition of harmonics distorts the sine wave as shown in the (Grady & Santoso, 2001)Figure 3:

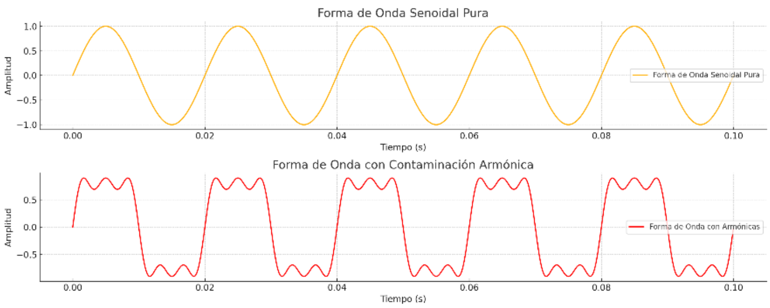

Figure 3 - Waveforms. In original language English

Source: The Authors (GeoGebra Interface)

These harmonics shown in the Figure 3 They can be generated by the presence of nonlinear charges in the electrical system. Harmonics in alternating current (AC) power systems can cause several adverse effects: excessive heating in transformers and electric motors, electromagnetic interference, voltage waveform distortion, and unwanted resonances. (Bollen & Gu, 2006) (IEEE, 2014)(Von Jouanne & Banerjee, 2001)(Rönnberg & Bollen, 2000)(Arrillaga, Watson, & Chen, 2000)(Akagi, 1998)

The analysis of harmonic contamination in hybrid inverters involves the evaluation of 4 key parameters: fundamental waveform, waveform distorts, total harmonic distortion (THD) and harmonic spectrum. For the fundamental waveform graph, the following equation will be used: (1) :(Hart, 2001)

$$V_{(t)=}V_{max} * sen(2\pi * f * t) \quad (1)$$

Where = Instantaneous value of voltage in time t, = Maximum amplitude of the sine wave, f = Frequency of the sine wave (60Hz), t = Time.$V_{(t)}V_{max}$

It is worth mentioning that the Equation (1) It is for the fundamental wave graph without harmonic distortion. The general equation to represent a harmonic-distorted wave, can be expressed as a sum of the fundamental wave and harmonic components (Fast Fourier Transform - FFT), as shown in Equation (2):(Hart, 2001)

$$V_{(t)} = \sum V_n * sen\left(k_n * 2 * \pi * f * t + \varphi_n\right) \quad (2)$$

Where = Instantaneous value of the voltage or distorted current in time t, = Amplitude of the fundamental component and Amplitude of the harmonic of order n, f = Fundamental frequency, = Order of the harmonic. The sum Σ extends to all harmonics present in the distorted wave.$V_{(t)}V_nk_n$

This Equation (2) expressed in a general way, allows to represent the distorted waveform and the harmonic distortion rate or THD, it is the relationship between the harmonic residual value and the fundamental component, expressed in percentage value as in the Equation (3) . (Téllez Ramírez, 2010)

$$THD(\%) = \frac{\sqrt{\sum V_n}}{Vfund} * 100 \quad (3)$$

Where the THD in percent represents the Total Harmonic Distortion, it represents effective values of harmonics of order n and is the effective value of the fundamental component. Then, in the V_nV_{fund}Figure 4 the periodic deformation of the voltage signal (THDv) or the current signal (THDi) is displayed:

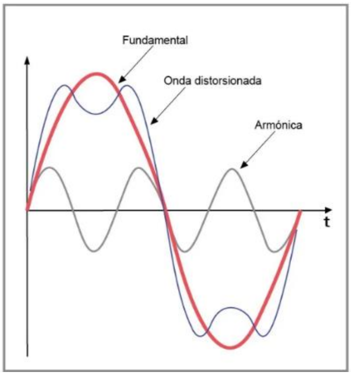

Figure 4 - Periodic deformation of the voltage signal (THDv) or the current signal (THDi). In original language English

Source: https://www.secovi.com/blog/3/distorsion-armonica-de-corriente-vs-distorsion-armonica-de-voltaje

On the other hand, the Figure 4 It shows the fundamental wave deformation and harmonic composition of the output signal. Shows the individual harmonic component present in the signal. For the mitigation of harmonic contamination in hybrid inverters, passive filters, such as LC filters, and active filters, which offer efficient dynamic compensation, are used.(Akagi, 1998)(Bollen & Gu, 2006)

2.3. Regulations and Standards

The control of harmonic contamination is essential today, due to the increase in nonlinear loads on networks. Organizations such as IEEE and in Ecuador, the Ministry of Electricity and Renewable Energy and CONELEC establish harmonic distortion limits.

The IEEE Std 519-2014 standard, entitled "Practice and Recommended Requirements for Harmonic Control in Electrical Power Systems", is recognized because it establishes harmonic distortion limits. The Board 2 presented below makes a summary of the regulations with the permissible limits on each individual harmonic for the voltage.

Board 2 - Voltage distortion limits at the common coupling point (PCC)

Voltage in the PCC	Single harmonic (%)	THD (%)
$V \leq 1$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5

Source: The Authors (IEEE Std 519-2014 Standard for Voltage THD)

The IEEE Std 519-2014 standard sets strict limits for total harmonic distortion (THD) presented in the Board 2. For low-voltage systems (less than 1 kV), the recommended THD limit is 8%. In medium-voltage systems (1 kV to 69 kV), it is reduced to 5%, and in high-voltage systems (69 kV to 161 kV), it is set at 3%. In Ecuador, CONELEC and ARCONEL regulate the quality of electrical energy and the levels of harmonic pollution allowed in the network. The ARCONEL 005/18 resolution sets limits for total harmonic distortion (THD) and individual harmonics, based on the IEEE Std 519-2014 standard. These regulations promote harmonic mitigation technologies and practices to improve the quality of the electricity supply based on the values of the (IEEE, 2014)Board 3.

Board 3 - Current Distortion Limits based on IEE and IEC standards

Ratio Isc/IL	Total Harmonic Distortion (THD) (%)	Individual Limit (%)
< 20	5.0	4.0
20 - 50	8.0	7.0
50 - 100	12.0	10.0
100 - 1000	15.0	12.0
> 1000	20.0	15.0

Source: IEEE Std 519-2014 Standard for Current THD

ARCONEL resolution 005/18 establishes the permissible limits of harmonic distortion in the Ecuadorian electricity grid as shown by the Board 3. These limits are in line with international recommendations and adapted to local operating conditions.

For the evaluation of the use of the harmonic filter, the following logic has been used for its calculation. The Figure 5 It shows the algorithm that continues to be taken into account that a common approach to implementing a harmonic filter is to use the Fast Fourier Transform (FFT) to convert the signal from the time domain to the frequency domain, manipulate the frequency components, and then use the Inverse Fourier Transform (IFFT) to return to the time domain. Research works such as the one in which we have implemented algorithms for the case of the current injection method and for the calculation of power flow and subsequent choice of filter. The algorithm that has been developed is specifically for the calculation of the filter, taking into account the work mentioned as a background for the development. This is how the algorithm in Figure 5 provides a basis for the calculation of harmonic filters in electrical systems. However, each system is unique and may require specific adjustments or additional considerations.(González Palau, Marreno Ramírez, Legra Lobaina, León Segovia, & Proaño Maldonado, 2016)

Figure 5 - Algorithm for filter calculation. In original language English

Source: The Authors (Publisher Interface 2019)

4. Analysis of Results

For the development of the study, the power quality analyzer has been connected for 7 days as recommended by the IEEE Std 1159-2019 standard. It should be clarified that the hybrid inverter as such does not have harmonic generation problems as shown by the Board 4:

Board 4 - Unloaded data from the Analyzer

Parameters	Value
THD Voltage	0%
THD Current	0%
Output Voltage	120V
Output Current	0A

Source: The Authors (Analyzer Interface Data)

From the data set forth in the Board 4 it is necessary to put the pressure that there is no harmonic contamination at the output of the hybrid inverter, the THD of voltage and current is 0%, so it is necessary to continue with the application of the method for the different cases of load types connected to the hybrid inverter.

4.1. LC Combined Load

An inductive load of 20 W, 15 W, 9 W, 45 W, 7 W] and 8 W has been connected to the hybrid inverter, powers of capacitive and inductive technologies, these loads are ballasts, transformers, laptop chargers and LED luminaires. These devices operate at 110-120 V and 60 Hz. From the Power Quality Analyzer, data can be retrieved from the real consumption of an active power of 99.1 W and 93.5 VAR of reactive power with a power factor (FP) equal to 0.727, a phase shift of 43 degrees, a frequency of 60 [Hz] and a current of 1.135 A. The waveform obtained shows typical characteristics of an LC combined load, with an evident distortion due to the inductive and capacitive components. These wavewarps are shown in the Figure 6:

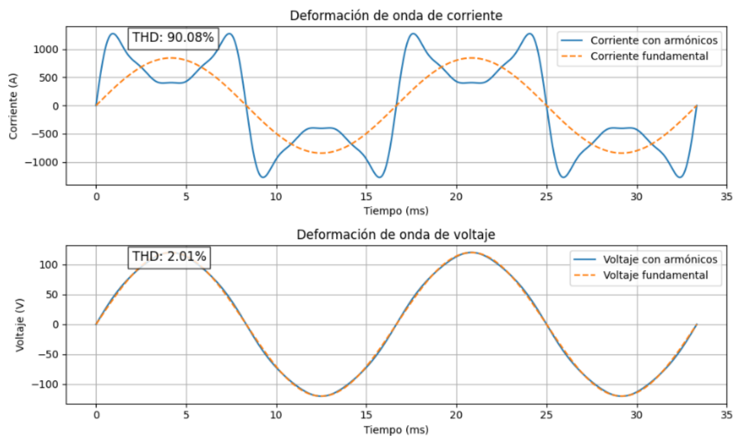

Figure 6 - Voltage and current waveform in LC loads. In original language English

Source: Power Quality Analyzer Interface

From the results presented in the Figure 6 and when compared with previous studies such as those that have reported similar THD values for LC loads, with current THD in the range of 50-80%. These studies also highlight that LC combined loads tend to exhibit higher distortion in current due to the resonance between the inductive and capacitive components. These current wave peaks are the ones observed in this study.(Smith, Johnson, & Lee, 2017)

Harmonic distortion with the use of nonlinear loads and electronic devices (LC) can generate harmonics of considerable amplitude such as those obtained in the measurements and shown in the Figure 7 Next:

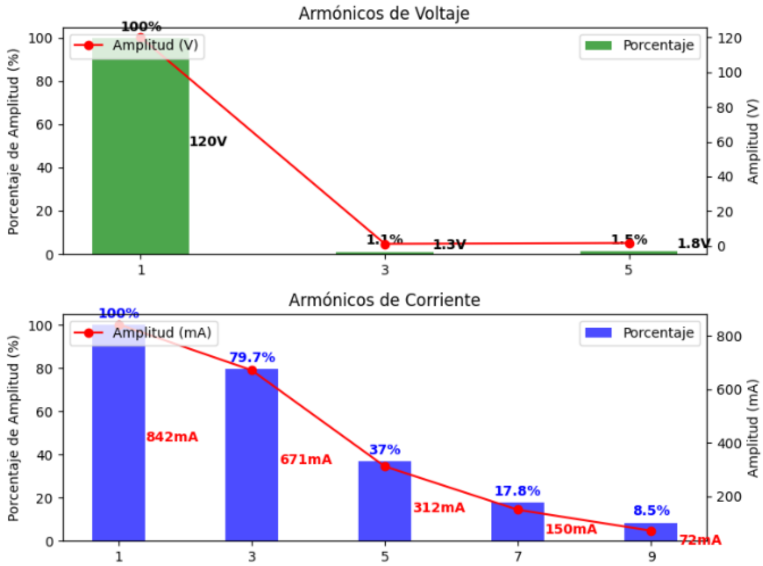

Figure 7 - Harmonic amplitude in LC loads. In original language English

Source: Power Quality Analyzer Interface

After evaluating the results of the Figure 6 and Figure 7, according to IEEE 519-2014, the voltage THD was found to be within acceptable limits (2.0%) according to the Board 2, while the current THD presents a value of 90.7 %, indicating a severe harmonic distortion when comparing this value with the data of the Board 3. Previous studies, such as those of , have documented similarly high current THD (50-80%) for LC loads, highlighting the effects that this generates. The 3rd, 5th, and 7th harmonicas are especially prominent. In these cases, authors such as recommend the use of passive filters tuned to these frequencies to mitigate the current THD.(Smith, Johnson, & Lee, 2017)(Sharma & Patel, 2024)

4.2. "Load Balanced" Analysis

Of all the devices that can be found in a residential electrical system, a combined load between resistive, capacitive and inductive devices has been connected to the hybrid inverter. The combined load data shows a real active power consumption of 359.4 W, reactive power of 56.3 VAR, voltage of 119.3 V, current of 3.049 A, FP of 0.988, a 9° offset, a voltage THD of 0.9%, and a current THD of 16.2%.

The presence of reactive components (inductive and capacitive) together with resistive ones, suggests a deviation from the pure sinusoidal waveform, a record that is observed in the Figure 8:

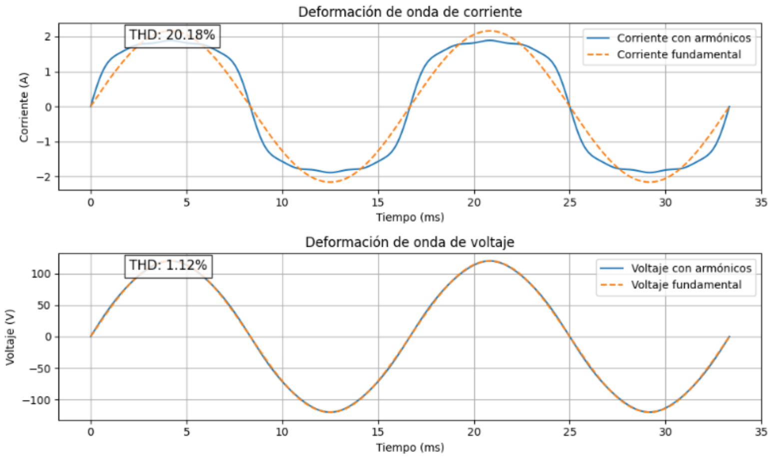

Figure 8 - Voltage and current waveform in RLC-type load. In original language English

Source: Power Quality Analyzer Interface

The waveform generated by the RLC load analyzed exhibits characteristics of high energy quality, with minimal distortion from the ideal sine wave, as shown by the Figure 8. However, it is important to perform a more in-depth analysis of harmonic components to ensure compliance with the strictest power quality standards. Here the RLC load has a very low voltage THD (0.9%) and a moderate current THD (16.2%), indicating the presence of harmonic distortions mainly in the current. The amplitudes of the most relevant harmonicas are presented in A Figure 9:

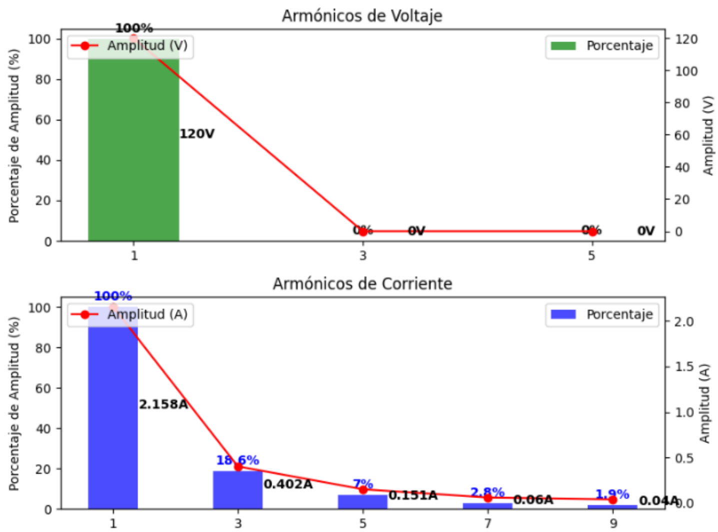

Figure 9 - Amplitude of current and voltage harmonics in RLC loads. In original language English

Source: Power Quality Analyzer Interface

In the study of , predominant harmonics of the third and fifth order were identified in similar RLC loads, with amplitudes of 0.15 A and 0.10 A respectively. Although our results of the (Ramírez, González, & Torres, 2019)Figure 9 show slightly lower values, possibly due to the specific configuration of the load and its high power factor close to unity, it was observed that the current THD exceeds the limits established by the Ecuadorian regulation ARCONEL 003/18, which specifies a maximum of 8% for industrial systems. It is then recommended to connect balanced RLC loads to reduce harmonic distortion and improve the power factor, although supplementing with passive or active filters may be required to fully comply with power quality regulations.(Ramírez, González, & Torres, 2019)

4.3 Use of harmonic filters for harmonic mitigation

In the calculation of the harmonic filter, the IEEE-1531-2003 standard has been taken as a reference, which establishes the following design principles:

- Tuning frequency: It is recommended to tune the filter to a frequency slightly lower than the frequency of the target harmonica (approximately 3% to 10% lower).(IEEE-1531-2003, 2003)
- Quality Factor (Q): A high quality factor (usually between 20 and 30) is recommended.(IEEE-1531-2003, 2003)

The following are the expressions used to perform the calculation of the passive filter in the following steps that have been used in :(Velásquez Tapia & Marreno Ramírez, 2014)

1) Calculation of the reactive power that needs to be compensated is given by Equation 4

$$Q_{eff} = \left(\tan_{\theta_1} - \tan_{\theta_2}\right) * P \quad (4)$$

Where Current FP Angle, Desired FP Angle, Active System Power.$\theta_1 = \theta_2 = P =$

2) Calculation of the effective reactance of the filter using the Equations (5) and (6) . For this case study, a 7% limit based on the IEEE-1531-2003 standard has been taken:

$$X_{eff} = \frac{(V_{LN})^2}{Q_{eff}} \quad (5)$$

$$X_c = \frac{(h-(h*0.07))^2}{(h-(h*0.07))^2-1} * X_{eff} \quad (6)$$

3) Calculating the capacitor with the Equation (7):

$$C = \frac{1}{2*\pi*f*Xc}[F] \quad (7)$$

4) Calculating the Reactor with the Equation (8) and (9):

$$X_L = \frac{X_c}{h^2} \quad (8)$$

$$L = \frac{X_L}{2*\pi*f}\ [H] \quad (9)$$

5) Calculating the filter resistance with the Equation (10):

$$R = \frac{X_L * (h - (h * 0{,}07))}{Q_f}\ [\Omega] \tag{10}$$

6) Verification of the standard using the following Equation (11):

$$\%MargCorriente = \frac{I_{TOTRMS}}{I_{fund}} * 100 \leq 135\%\ \text{de la}\ I_{fund} \tag{11}$$

The comparison of results with the incorporation of the calculated filters is shown in the Figure 10. When performing the calculations for the harmonic filter application using Python programming language, a value of 2mH for the inductor and 100µF for the capacitor is obtained, as shown by the Figure 10. It should be noted that an adjustment has been made to obtain almost the same THD value of 16.2% current as the proposed use case.

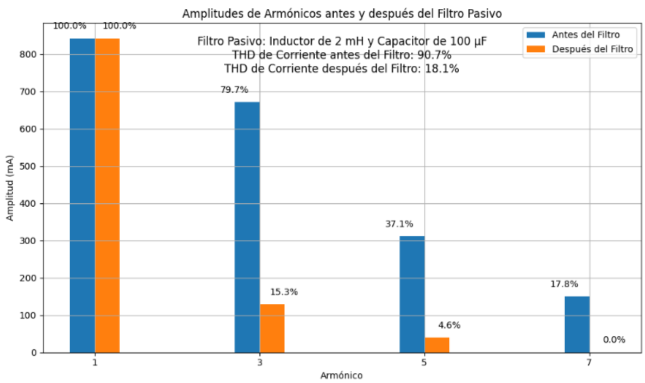

Figure 10 - Harmonic filter application results. In original language English

Source: Visual Code

To verify the effectiveness of the filter, we proceed to compare the value of Harmonic Current Distortion using the Board 3 of the IEEE Std 519-2014 standard. To calculate the short-circuit current, the following equation is used: (12):

$$Icc = \frac{V}{Zred} \tag{12}$$

Where Icc = is the short-circuit current in amperes, V= is the supply voltage between phase and neutral in volts, Z = is the impedance of the circuit in ohms.

Table 6 shows that the Isc/IL ratio is calculated with the following equation (13):

$$Ratio = \frac{Isc}{IL} \tag{13}$$

When performing the calculations of the Equation (12) a value of 35 A is obtained and from the Equation (13) a ratio value of 1.25. When referring to the values of the limits of the Board 3 an individual current THD value of 4% should be obtained. For the case study, Figure 9 identifies a current THD value for the third harmonic of 15.3 %; a value of 4.6% in the third harmonic, achieving compliance with the IEEE Std 519-2014 standard only the fifth harmonic. It should be clarified that the calculated harmonic filter was adjusted to obtain similar mitigation values as the practical proposal. The two proposals seek to be adjusted as a viable economic measure depending on the means in which it can be implemented.

For a better choice of the proposal to be implemented according to the means in which its execution is required, it is shown in the Board 5 Loss data in the two cases evaluated for the improvement of power quality in the network:

Board 5 - Loss Power

Active power losses	Case 1 (Load Balanced)	Case 2 (Tuned Filter)
Pp	0.499 W	0.357 W

Source: The Authors

From the information of the Board 5 it should be clarified that in Cases 1 and 2 in the presence of nonlinear loads, the difference between the losses can be noticed. In Case 2 a greater decrease is seen, reaching a value of 6% with respect to the initial condition of the system without the application of improvements. This is because the filter achieves a greater reduction in total harmonic distortion. By reducing harmonic currents, heating losses in conductors and equipment are minimized. Improvement of the power factor and by reducing losses, it improves the overall performance of the electrical system as corroborated by the study of . It is necessary to clarify that when calculating the filter, we tried to adjust its value as close as possible to the results obtained from the "Balanced Load" proposal.(Sharma & Patel, 2024)

5. Discussion of results

Various sources of harmonic distortion were identified under different load conditions. Higher-order harmonics, generated primarily by devices connected to the inverter. This is in line with previous studies such as those by , , , , and which point to inverters and other electronic devices as primary sources of harmonics in renewable energy systems. (López, García, & Pérez, 2021) (Petel, Joshi, & Sharma, 2014)(Pereira, Aredes, & Monteiro, 2014)(García, Rodríguez, & Pérez, 2018)(Smith, Johnson, & Lee, 2017)(Ramírez, González, & Torres, 2019)

The presence of harmonics was associated with a significant reduction in the efficiency of the electrical system between 5% and 6% respectively for the two chaos of improvements analyzed. The experiments showed that higher-order harmonics are prominent under different load conditions, highlighting the importance of mitigating harmonic contamination to optimize system performance. The use of specific filters for each identified harmonic was evaluated, demonstrating that passive filters designed to attenuate specific frequencies are effective in reducing harmonic amplitude and improving the quality of the energy supplied.

Another proposal is the implementation of the so-called "Balanced Load". This technique helps to evenly distribute the loads, thus reducing the effects of harmonics, it does not require additional investment, but it is subject to the possibility of being able to balance the use of the different types of loads, an aspect that may not always be feasible

6. Conclusions

Analysis of harmonic contamination in the output of a 3kVA hybrid inverter revealed that the main sources of harmonic distortion are due to variations in load conditions. These distortions have a negative impact on the efficiency of the system and the application of corrective measures can be reduced by 5% to 6% depending on the method applied.

Detailed measurements using power quality analysis equipment showed that the third, fifth, and seventh order harmonics are the most prominent in the hybrid inverter output. The magnitude of these harmonics varies with load and operating conditions, being more significant under Inductive-Capacitive load conditions.

The implementation of mitigation strategies recommended and implemented by other authors, such as passive filters and the case proposed in this study, demonstrates the same degree of effectiveness of the passive filter to considerably reduce harmonic distortion levels from 79.7 % to 16.2 % in the third harmonic, from 37.1 % to 4.6 % in the fifth harmonic. thus improving the quality of the energy supplied by the inverter. It has also been verified that the use of balanced load can be another way to solve pollution levels in cases where it is possible to move the use of certain loads over time. In turn, these results offer practical guidance for improving the efficiency and reliability of modern electrical systems in the presence of nonlinear loads.

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