Study of electric power quality indicators by simulating a hybrid generation system

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ABSTRACT

Currently, as part of the distributed generation paradigm, photovoltaic energy has a growing development. The diversity of the loads, their nonlinearity, and the penetration of the renewable energy sources (RES) cause a worsening of the energy quality indicators. The main quality indicators that affect hybrid photovoltaic systems are voltage and current harmonic distortion, voltage deviation, and voltage and current asymmetry in the system. The construction of physical and mathematical models in software applications, such as MATLAB, Simulink, and Simscape, makes it possible to simulate the operating conditions of these systems and determine the values of the indicators that account for the quality of the electric power supplied. In this work, the modeling and simulation of a photovoltaic system connected to the network that feeds a mixed industrial area are carried out to determine the indicators of energy quality.

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1. INTRODUCTION

Currently, 95% of electrical energy production in Cuba is based on the use of fossil fuels. As part of the approved policy for the perspective development of renewable energy sources and the efficient use of energy, a strategy is proposed to make the most of the renewable resources available in the country [1]–[4]. A hybrid system arises when two or more power generation systems are combined in a single installation to generate electrical power. These systems are generally composed of renewable energy sources (RES), and if necessary, they are complemented with generators, leaving them in most cases only for emergency functions [5]. In general, hybrid systems have advantages; among these are reducing the CO_2 emission associated with the generation of fossil fuels and reducing the environmental impact caused by electricity generation [6]. Hybrid systems provide significant improvements in those overloaded networks by increased consumption. Its implementation does not require substantial civil work. It reduces the costs associated with resizing the low voltage (LV) distribution networks by coupling reliable electric power generators, which use renewable resources and are sustainable over time.

The most common systems today are photovoltaic hybrids supported by a fossil fuel generator (generator set) [5]–[9]. However, hybrid systems with photovoltaic generation are frequent, whose primary energy source is the electricity grid. These systems offer the possibility of reducing the operating cost of the facilities by reducing the electricity consumption of the network (and even covering the inputs) in the hours of the most excellent solar radiation [5]–[9]. In those cases, energy storage systems can guarantee part of the necessary energy during the night. Hybrid systems also represent a backup against electrical interruptions in the system. In photovoltaic systems (PV) connected to the grid, the fundamental element to control is the three-phase inverter. The control strategies of the inverters are based on the shaping of the excitation or firing signal of the semiconductors that act as controlled switches. In this way, it is possible to operate on the voltage waveforms at the output of the inverter, guaranteeing that they are within the parameters of amplitude, frequency, and phase displacement regulated for the alternating current (AC) system belong.

In a photovoltaic system (PV), the waveform of the current and voltage signals on the AC bus can be impaired for different reasons, the most common being the nonlinearity of the loads downstream of the common point of connection (CPC), which demand nonlinear currents from the system and can distort the voltage waveform [10]–[12]. Another because that distorts the signal is the presence of harmonics and unbalance in the secondary distribution network due to using single-phase transformers of different capacities that form three-phase banks. The current and voltage distortion in the distribution network can be reflected in the transformer's secondary depending on the connection scheme [13]–[16]. Finally, the distortion in the waveform of the voltages at the output of the inverter, caused by the conversion of a DC system into AC, can be another cause that distorts the current and voltage signals on the AC bus [17]–[19].

Due to these causes, it is that the quality of the power in the PV with connection to the network is given by three fundamental indicators. The first is the individual harmonic distortion and total harmonic distortion (THD) of the voltages (THDv) and the currents (THDi) [20]. The second indicator is given by the deviation of the voltages (U_d) for the rises (U_{ds}) and falls (U_{db}), presented by the relationship between the practical value of the voltage at a point concerning the nominal value for the system [21]. The third and last indicator refers to the asymmetry due to the unbalance in the voltage and current signals given by the relationship between the symmetrical components of the null sequence and positive sequence for the voltages and currents of the system [22].

Kulikov *et al.* [23] carried out a study of the quality indicators of electrical energy in medium and high voltage distribution networks integrated with renewable energy stations that use solar photovoltaic energy and wind energy, concluding that critical deviations from the normal operating values of the power quality indicator may occur under low load conditions in the inverters/converters. To solve this problem, they propose a device for the sampling control of the electric power quality indicator that automatically detects existing deviations. In [24], a novel strategy based on genetic algorithms (GA) is presented to design an independent solar PV system with an optimal system size that meets power quality standards. The MATLAB/Simulink environment was used to develop a detailed model of a solar PV system, including a robust control mechanism for maximum power point tracking, bidirectional battery control, and inverter output control. The simulation results show that ignoring power quality criteria by selecting inappropriate and sub-optimal system parameters can lead to unacceptable voltages and THD levels.

According to [25], higher photovoltaic (PV) integration can affect both voltage and current quality in low-voltage (LV) power grid operations, so the authors evaluate the influence of PV according to the behavior of various parameters and power quality indicators at the common coupling point in a low voltage network. The steady-state power quality parameters evaluated are RMS voltage (VRMS), reactive power (Q), total and harmonic components of voltage (THDv, Uh) and current (THDi, Ih), voltage unbalance (Desbv) and total rated current distortion (TRD). The results indicate that Q, Desbv, and TRD comply with the reference values in each emulated scenario. However, the following P&Is do not meet the reference values of 66.67% VRMS, 26.67% THDv, and 100% THDi. Furthermore, in all scenarios, Uh and Ih does not satisfy at least one harmonic component requirement, mainly the fifth and/or seventh harmonic components.

In correspondence with this, it is necessary to adopt technical measures that allow raising the indicators of energy quality in photovoltaic systems with grid connection. The creation of a model for the simulation of these systems would make it possible to determine the power quality indicators from the digital processing of the voltage and current signals in the AC bus, considering the nonlinearity of the loads downstream of the point common connection of the photovoltaic system with the grid. From the implementation of technical improvements, it is possible to evaluate the impacts on a simulation scale, in the technical order, linked to the reduction of losses, and in the economic order, in the reduction of the operating costs of these systems.

2. METHOD

The electrical supply of the general hospital "Dr. Juan Bruno Zayas," in Santiago de Cuba, Cuba, comes from the national electrical system (NES) and is carried out through two primary distribution circuits at 13.8 kV that energize a bank of 3 three-phase 1000 kVA transformers with a Δ/Y connection grounded. the hospital has two-man generators of 712 kVA, with a power factor of 0.8. These generating sets are connected as backup or emergency in case of absence from the SEN and only supply power to the first category or essential loads. The PV with connection to the surgical clinical general hospital "Dr. Juan Bruno Zayas" network has been operating continuously since 2016, with a total installed power of 100 kWp. This photovoltaic system has four three-phase inverters SMC 7000 HV-11. Each inverter is associated with 96 photovoltaic panels divided into four parallel branches of 24 PV with a generation of 250 Wp each, Figure 1. In 2019, a joint study was carried out with the national office for the control and rational use of energy, which revealed problems related to imbalance and THDi shown in Figure 2.

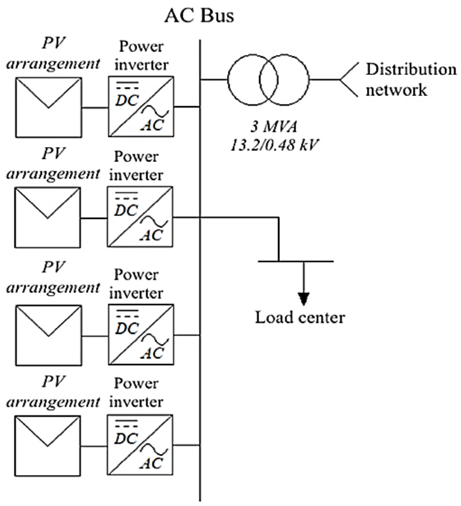


Figure 1. Diagram of the hybrid system with PV generation connected to the hospital network

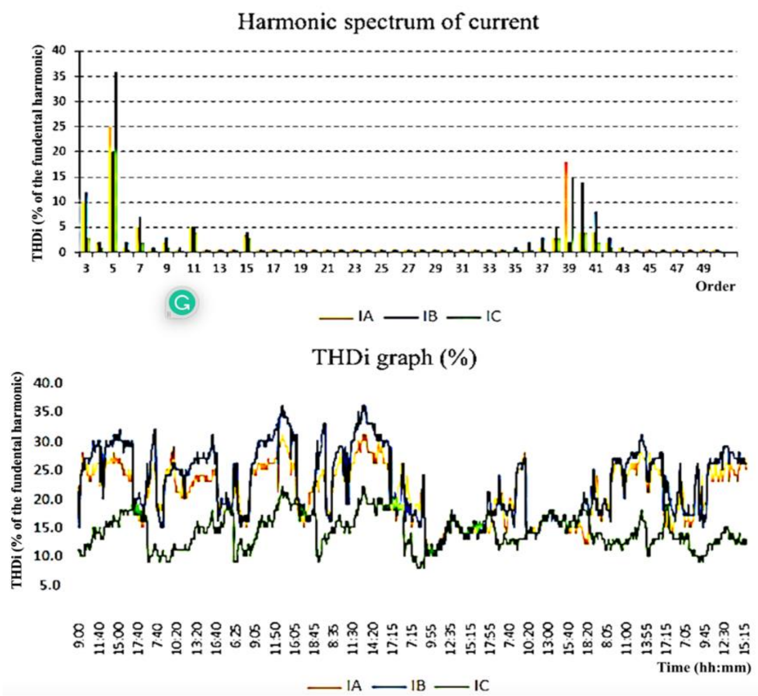


Figure 2. Graph of the evolution of THDi and the harmonic spectrum of currents during a typical day on the AC bus of the hospital "Juan Bruno Zayas"

2.1. Indicators of power quality in low voltage networks

Systems can be evaluated from product quality or waveform quality of voltage and current signals. To establish a quality criterion, a set of standardized indicators is considered for the different tension levels. Indicators include waveform distortion, voltage, and current harmonics, crest factor, voltage fluctuations or flicker, voltage deviations, frequency deviations, and unbalance in voltages and currents [10]–[13].

According to the IEC 61000-3-4 standard [26], the expression that allows determining the percentage of unbalance in the voltage is given by (1).

$$\text{khd} = \frac{Ua_2}{Ua_1} \cdot 100 \quad (1)$$

Where khd is the asymmetry or imbalance coefficient, in this case, the stress, expressed in %; U_{a1} and U_{a2} are the amplitude values, or the RMS voltage values of phase for the positive and negative sequence, respectively. The voltage rises (U_{ds}) and falls (U_{db}) are quantified as shown in (2) and (3).

$$U_{db} = \frac{U_n - U_r}{U_n} \cdot 100\% \quad (2)$$

$$U_{ds} = \frac{U_r - U_n}{U_n} \cdot 100\% \quad (3)$$

Where U_n is the nominal voltage (V); U_r is the actual voltage (V); U_{ds} is the deviation per upload (%), and U_{db} is the deviation per descent (%).

The Cuban electrotechnical code (CEC), in the Cuban standard NC 800-1: 2011 [27], defines the normalized voltages for the industrial and tertiary sectors. In the case of voltage deviations, it establishes that the variations must not exceed ±10%. Frequency variation means the system's fundamental frequency deviation from its specified nominal value. According to the Cuban standard NC 800-1: 2011 [27], it is established as a nominal frequency of 60 Hz and its allowable deviations of ± 1%. These fluctuations may be more significant when emerging generators and isolated, autonomous networks are used.

The IEC 61000 Standard on electromagnetic compatibility (EMC) sets the limits for harmonic distortion of voltages (IEC 61000-2-2) [28] and currents (IEC 61000-3-4) [29] in an electrical system of LV and currents less than 16 A. According to IEC 61000-2-2, the corresponding compatibility level for total harmonic voltage distortion is THDv = 8% for long-term effects. For distribution systems, IEEE Standard 519-1992 [30] is used, which sets the limits of harmonics that can be produced and circulated through the electrical system for voltages higher than 120V and lower than 6.9 kV. According to the IEEE 519-1992 Standard, the THD value for voltages on the AC bus should not exceed 5%, while for currents, it should be governed by Table 1.

Table 1. Harmonic distortion limits for percent load currents for distribution systems

I_{cc} / I_L	Harmonics order (Odd harmonics)					Total distortion demand (TDD)
< 20*	2-11	12-16	17-22	23-34	> 34	5
20 < 50	4	2	1.5	0.6	0.3	8
50 < 100	7	3.5	2.5	1	0.5	12
100 < 1000	10	4.5	4	1.5	0.7	15
> 1000	12	5.5	5	2	1	20

(*) For all generation equipment, regardless of the I_{cc} / I_L ratio. I_{cc} is the short-circuit current in the common point of connection (CPC) or AC bus, A, and I_L is the load current on the CPC or AC bus, A.

2.2. Model for simulating PV with grid connection

Digital simulation allows the construction of an abstract model, starting from a real system, which is especially useful when studying the system's behavior. The model allows evaluation of the studied microsystem's quality indicators from the digital simulation using MATLAB/Simulink as a software tool. MATLAB software is an ideal tool for simulating physical elements from iconic, symbolic, and mathematical models using functional blocks that allow interaction as a whole to study the behavior of a system over time, allowing static and dynamic simulation. In addition, MATLAB allows the interaction of these functional blocks with codes of its programming language, which provides greater potential in the analysis and use of the graphic potential of the software. Based on the diagnosis and the study results, it is possible to build a model that simulates the hybrid system in different scenarios and determines its quality indicators by implementing technical improvements to reduce them. Figure 3 shows the model implemented in MATLAB/Simulink/Simscape.

The functional blocks of this model are detailed below, where the photovoltaic solar array (PV array), the three-phase inverter (universal bridge), the PWM (inverter control) signal generator, the three-phase load, and the block to simulate the grid distribution, are the main elements of it.

The array of photovoltaic solar panels consists of 16 branches connected in parallel, with 24 solar panels in series each, for a total of 384 panels. Each photovoltaic panel has a power of 250Wp for a total installed capacity of 96 kWp. For the implementation of the inverter, a three-arm H-bridge type three-phase inverter is used, based on an insulated gate bipolar transistor (IGBT) with a diode in an antiparallel connection. The control module will be in charge of generating the pulses with a square waveform for the control of the converter using pulse width modulation (PWM). The distribution network is simulated as a source of constant voltage and frequency.

The values of the measurements made in the system are used to model the nonlinear load. In this case study, measurements were made for a week, with measurements between 06:30 and 18:00, using a Chauvin Arnoux CA 8332 recording instrument. The system loads have been separated into balanced three-phase loads, with a power of 610 kVA and a lagging power factor of 0.98. To simulate the nonlinear component of the load, an arrangement of controlled current sources has been used according to the harmonic spectrum obtained from the study carried out, Figure 4.

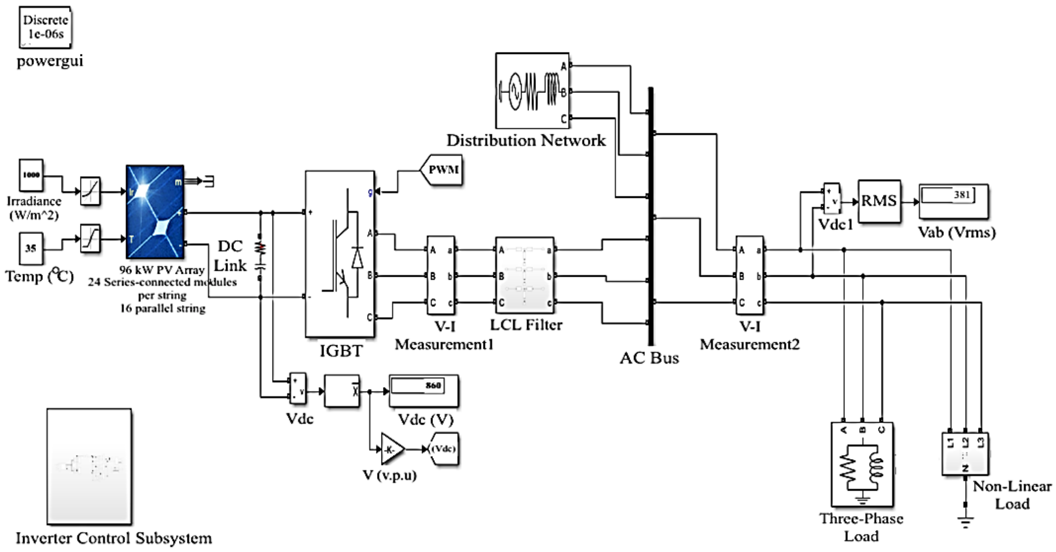


Figure 3. Model to determine the quality of energy in a hybrid system with a connection to the grid

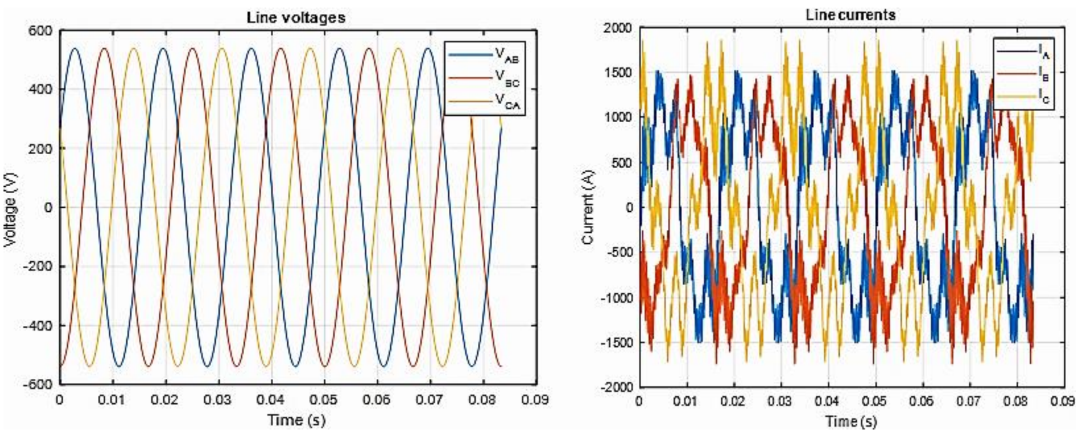


Figure 4. Waveforms of line voltages and currents on the system AC bus

The analysis reveals that the THDv does not exceed 1%; however, high THDi values range between 36.7% and 47.6%, Figure 5. The predominant harmonics are orders 3, 5, 7, and 11. The amplitude spectrum reveals a high distortion in the harmonics between orders 38 and 41. In all cases, the values exceed the limits for individual harmonics given by IEEE standard 519-1992, see Table 1 [30]. The model obtained can determine the value of the quality indicators of the system for a given operating point from the processing of the voltage, current, and power signals on the AC bus. No significant results are shown in the processing and calculating of the power quality indicators in the SFV with connection to the grid. The asymmetry values for voltages and currents and the voltage and frequency deviation are well below the standardized limit values. However, the power factors per phase are considerably low, causing the system to operate with an overall power factor equal to 0.71.

Even though the power factor is not an indicator of electrical energy quality, it constitutes an indicator of electro-energy efficiency. Its improvement quickly leads to tangible economic and technical benefits with short investment returns. On the other hand, the reagent compensation for increasing the power factor in an industrial electrical installation is beneficial in terms of quality, contributing to the suppression of harmonics and improving the voltage profiles.

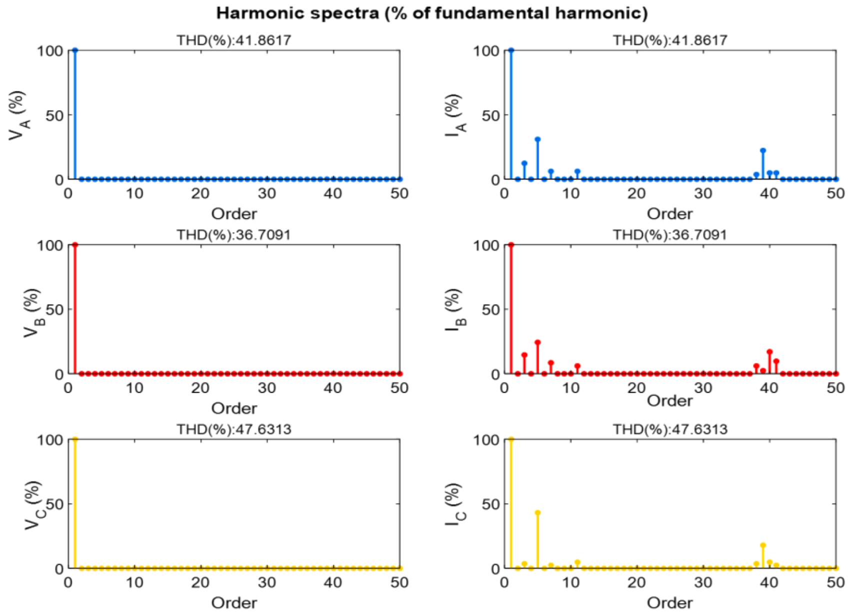


Figure 5. Harmonic spectra and THD values for voltages and currents on the AC bus

3. TECHNICAL IMPROVEMENTS FOR QUALITY INDICATORS

A reagent compensation method is used through a bank of capacitors connected in parallel to raise the value of the power factor with which the system operates. The value of the capacitor bank to be placed depends on the power and power factor values registered on the AC bus and the desired power factor. The value of the desired power factor will be 0.98 (the upper limit value of the bonus by the electric company in Cuba). The calculation of the reactant demanded by the system, after compensation, and the capacitive reactant that must be injected into the network can be calculated utilizing expressions (4) and (5).

$$Q_2 = P_1 tan\left(cos^{-1}(FP_2)\right) \quad (4)$$

$$Q_C = Q_1 - Q_2 \quad (5)$$

Where Q_2 is the reactant demanded by the system after compensation (kVAr); P_1 is the active power required by the system (kW); FP_2 is the desired power factor (0.98); Q_c is the capacitive reagent that needs to be injected into the network (kVAr); Q_1 is the reactant demanded by the system before the kVAr compensation. The capacitive reagent that must be injected into the network will be 460 kVAr, for which a three-phase bank of capacitors with a Δ connection will be used in the form of centralized compensation, Figure 6.

The reagent compensation in the system has raised the power factor from 0.71 to 0.93, representing a significant technical and economic result for the entity. This improvement results in the THDi values for the currents being reduced compared to the circuit without compensation, ranging between 33.8% and 41.75%. Despite the reduction represented by the connection of the capacitor bank in parallel, which acts as a first-order low-pass filter, the THDi values continue to be excessively high, so additional technical measures are required.

To reduce the harmonic distortion values, it is possible to use passive filters in the system [31]. Harmonic filters reduce the flow of harmonic currents through the system by improving the waveforms of currents and voltages. Passive filters are connected in parallel and are made up of a capacitor in series to an RLC circuit with an impedance that is a function of the frequency of the harmonic to be filtered. The harmonics to be filtered are in orders 3, 5, 7, 39, and 41. For this, two double-tuned filters [32] will be used for harmonics 3 and 5 and 39 and 41, respectively. The 7th-order harmonic will be attenuated using a single-tuned filter [33]–[37]. The filters designed and implemented in MATLAB/Simulink/Simscape are detailed in Table 2 and Figure 7. The filter bank circuit for the attenuation of harmonics in the load is shown.

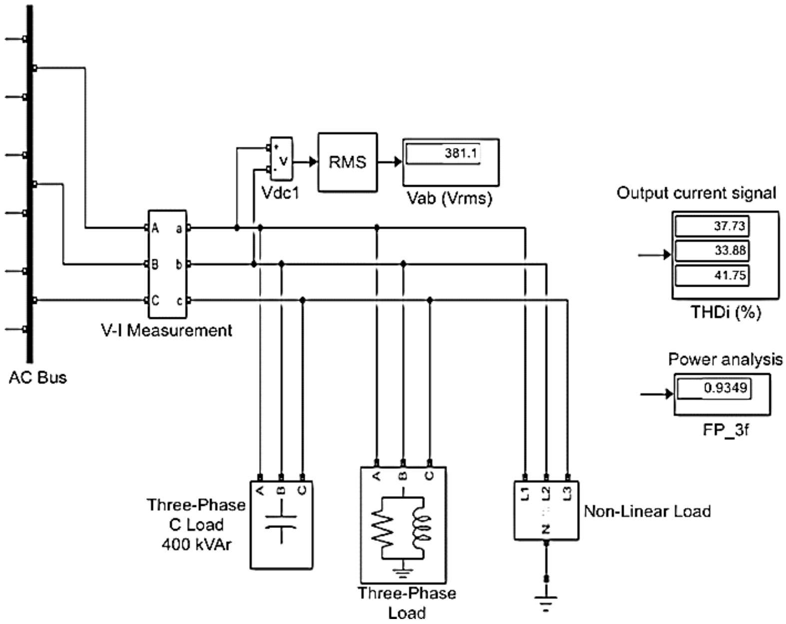


Figure 6. Centralized reagent compensation using a 400 kVAr capacitor bank

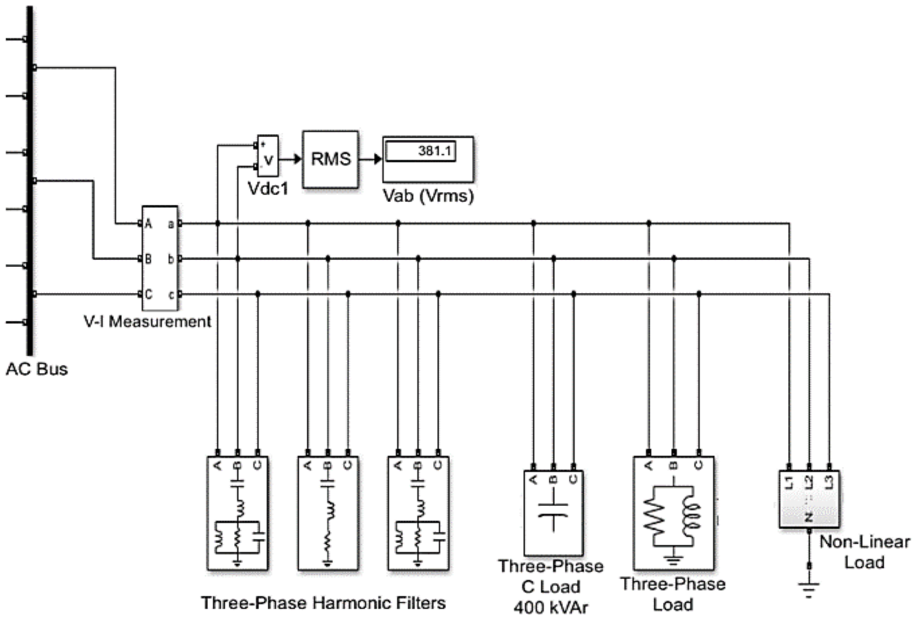


Figure 7. Filter bank for the attenuation of harmonics in the load

The simulation results are detailed in Figure 8, where Figure 8(a) shows the waveforms of the line current signals at the output of the three-phase passive filter bank, and Figure 8(b) presents the spectrum harmonic of said line currents. In this figure, the harmonic distortion of the currents has been considerably reduced (see the current waveform and the harmonic spectrum in Figure 4 without affecting the quality of the rest of the system indicator.

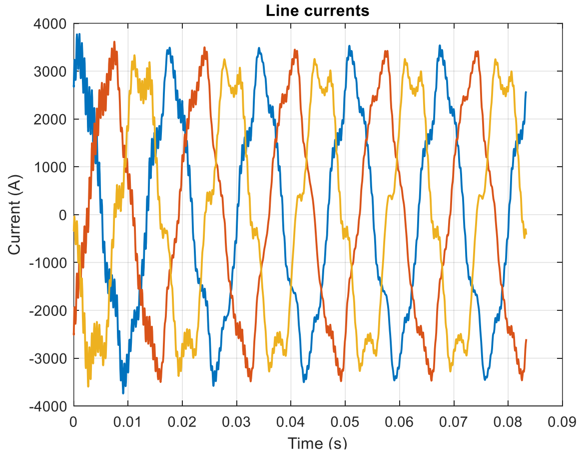
Table 2. Design values of the filters used in the simulation

Filter	Order (n) of the harmonic to filter $(n \cdot f_1)$	Nominal line voltage (V_L)	Reactive power (Q_r)	Quality factor (Q)
Double tuned	3 and 5	380 V	40 kVAr	20
Single tuned	7		60 kVAr	20
Double tuned	39 and 41		20 kVAr	20

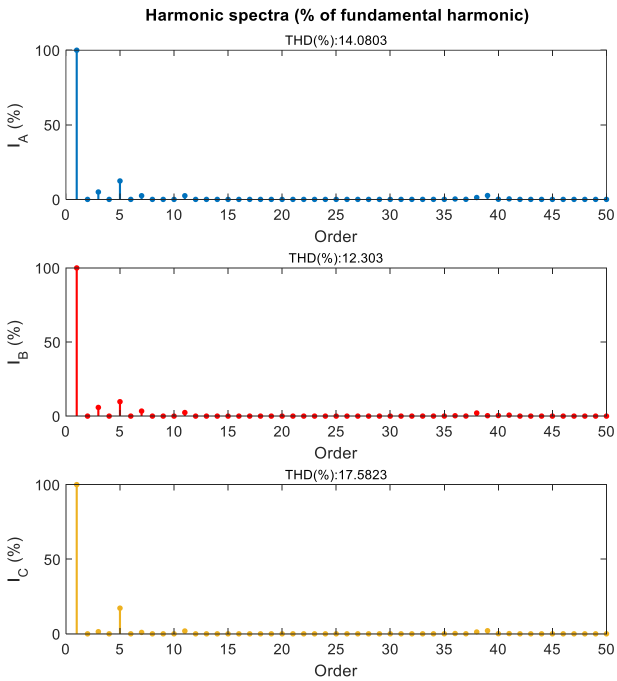
Table 3 shows the comparative values of the three simulations, demonstrating that reducing the harmonic content in the line currents using filtering improves the wave quality during the system's operation without worsening the rest of the quality indicators. The technical measures proposed in the system entail a cost per investment which the effect on efficiency must justify during its operation. To explain this increase in efficiency, the impact of harmonics on the deterioration of the equipment and the reduction of its useful life, the oversizing of the system elements, and the increase in losses that the consumer entity must pay for must be estimated.

Table 3. Summary of results of the simulations of the SFV with connection to the network

PV scenarios	FP	THDi (%) (average)	THDv (%) (average)	U_{bd} (%)	khdv (%)	khdi (%)
Actual state	0.71	42.06	0.10	$7.23{\cdot}10^{-3}$	$6.4{\cdot}10^{-12}$	$2.17{\cdot}10^{-5}$
With reactive energy compensation	0.93	39.16	0.13	$8.92{\cdot}10^{-5}$	$2.9{\cdot}10^{-13}$	$5.01{\cdot}10^{-5}$
With reactive compensation and harmonic filtering	0.94	14.49	$1.49{\cdot}10^{-6}$	$6.51{\cdot}10^{-5}$	$4.25{\cdot}10^{-13}$	0.03



(a)



(b)

Figure 8. Line current signals at the output of the three-phase passive filter bank in (a) waveforms and (b) harmonic spectrum

4. CONCLUSION

The PV study with connection to the network of the hospital general Clínico Quirúrgico "Dr. Juan Bruno Zayas" in Santiago de Cuba, Cuba, shows that the power quality indicators related to the frequency deviation, the deviation of the voltages, the unbalance of the voltages and currents as well as the THDv, maintain their values below the limits that govern technical standards, as these indicators are linked to the robustness of the electrical network.

The use of multilevel inverters and inverter output filters guarantees a waveform for the voltages on the AC bus that is practically sinusoidal. The existence of nonlinear charges is a factor that contributes to the deterioration in the waveform of current signals. The average THDi value obtained in the study is 42.06%. The simulation of the microsystem reveals that the THDi values range between 36.7% and 47.6%. In the case of individual harmonics, the limits given by IEEE standard 519-1992 for components of orders 3, 5, 7, 11, 39, and 41 are exceeded.

A significant result is in the value of the power factor registered in the AC bus, 0.71. The technical improvements proposed to the microsystem involve the compensation of the inductive reagent using a bank of capacitors in parallel. Reagent compensation allows the power factor to be raised to 0.93. Finally, the technical improvement for suppressing current harmonics uses double tuning filters for harmonics 3 and 5 and 39 and 41, respectively. In contrast, a tuned filter is used for harmonics of order 7. The simulated results of the improvement show the reduction of THDi up to 14.49%, which demonstrates the advance's effectiveness and contributes to a modification of the power factor, raising it to 0.94.

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