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**Article**

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# Influence of Photovoltaic Systems on Power Quality Problems

**Yohan Sanchez-Puentes[1], Christian Argote-Parra[1], Waddy Lakatt-Benavides[1], Jaider Narvaez-Viana[1], Jose Nuñez-Alvarez[2], John Grimaldo-Guerrero[2]***

[1]Estudiante de Ingeniería Eléctrica, Universidad de la Costa, Colombia, [2]Departamento de Energía, Universidad de la Costa, Colombia. *Email: jgrimald1@cuc.edu.co

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**ABSTRACT**

Photovoltaic (PV) systems have been rapidly implemented in commercial facilities without determining the negative impacts that may result when connected to the facilities' electrical power system. The research presented shows the results of a study of the quality of electrical energy in a commercial installation in which there were no problems before implementing the PV system. Measurements of different parameters of the energy generated by the photovoltaic system and that provided by the electrical network are carried out, carrying out a simulation using the Helioscope software. As a result of the work, voltage variation and current harmonics problems are identified, carrying out a technical and economic analysis of implementing a passive filter that performs the respective corrective actions.

**Keywords:** Photovoltaic systems, Power quality, Voltage variation, Current harmonics, Electrical network.
**JEL Classifications:** C63, L94, Q4.

## 1. INTRODUCTION

Necessary research on energy development using Non-Conventional Energy Sources (NCES) is carried out every day due to the benefits of its introduction, the diversification of the energy matrix, and the effects on the environment. Using these energies not only helps reduce the emission of greenhouse gases but also helps conserve energy for future use (Anaadumba et al., 2021). However, some researchers discuss integrating the NCES while guaranteeing a stable, quality supply that can be competitive with conventional energies (Epeni-Tombo et al., 2023; Merchán et al., 2020; Moreno et al., 2022; Rodríguez-Gámez et al., 2022).

According to the International Renewable Energy Agency (IRENA) statistics, the NCES added 167 GW to the global scale in 2017, representing an increase of 8.3% compared to the previous year (IRENA, 2018). In addition, according to the International Energy Agency (IEA), the global electricity supply will increase drastically in the next two decades; estimating that 44% of the generation in 2040 will come from the NCES, mainly to wind and photovoltaic energy, due to mainly because its generation costs have been reduced by up to 73% (IEA, 2020).

In the case of Colombia, photovoltaic (PV) systems, despite being developed since the 1970s, were not widely implemented until 2015 (Rodríguez Murcia, 2008), when Law 1715 of May 2014 came into force, establishing a series of incentives for this type of project; it was reflected in an increase of 90% of the PV projects registered with the *Unidad de Planeación Minero Energética* (Radomes and Arango, 2015), translated as Mining-Energy Planning Unit. Consequently, a more significant number of residential or commercial PV installations connected to the power grids of different grid operators will affect power quality (Radomes and Arango, 2015; Rodziewicz et al., 2021).

Electrical networks experience various problems with the quality of electrical energy. In most cases, they are caused by the entry into service of large loads with non-linear behavior, such as variable speed drives, motors or welding equipment, light emitting diode lamp circuits, or PV systems (Grau et al., 2021; Silva et al., 2019).

The quality problems of electrical energy that can manifest due to the connection of PV systems are related to the characteristics of these systems in the generation process, which usually manifests itself in voltage and current imbalances, in addition, to a linear component in the waveform after the rectification process, which added to non-linear loads connected to the system, can cause harmonics, power factor displacements, and power quality problems at the point of connection with the network operator (NO) (de Cerqueira Lima e Penalva Santos et al., 2022; Girigoudar and Roald, 2020).

This research work is intended to determine the behavior of the power system of a commercial installation with problems of quality of electrical energy, which are evidenced by having a higher than average energy consumption. Based on the electrical measurements carried out, the effect of the energy generated by a PV plant with a synchronous connection to the local electrical network is evaluated to mitigate or spread the problems associated with the quality of energy in the network. In addition, alternatives are proposed to correct energy quality problems. A relationship is established between implementation costs, system losses, and generated profits.

## 2. METHODOLOGY

A commercial installation is evaluated in which a 100 kWp PV system is installed, with a synchronous connection to the NO to sell surplus energy and consume energy in low-generation scenarios. Taking the above into account, constant voltage variations and an increase in expected energy consumption after the implementation of the PV system have been evidenced. In addition, since there is no constant monitoring system, a network analyzer (AR) device is installed, as seen in Figure 1.

Two measurements are made with the AR METREL MI 2892 type network analyzer, the first with a duration of 3 days at the output of the set of inverters and the second with a duration of 5 days in the low voltage winding of the main transformer, of so that there are two reference points to establish the electrical behavior of the installation. In addition, the Helioscope software is used to obtain the theoretical generation of the plant for 1 year.

To determine the state of the power quality losses at the two points evaluated, the frequency variation is initially verified according to the criteria of NTC 1340, taking measurements every 10 s and using a frequency range between 59,8 Hz and 60,2 Hz (*Norma Técnica Colombiana NTC 1340 - Electrotecnia. Tensiones y Frecuencia Nominales en Sistemas de Energía Eléctrica en Redes de Servicio Público*, 2013; Silva Ortega et al., 2016). Similarly, the nominal value of the voltage can be 5% above and 8% below.

On the other hand, as established in the IEEE 519 Standard, for voltage levels below 1 kV, individual short-duration harmonics must be <5%. Their harmonic distortion must be <8% (Institute of Electrical and Electronics Engineers., 2014; Vlasov et al., 2022). Table 1 shows the distortion limits for nominal voltages between 120 V and 69 kV, which must be expressed as a percentage of the maximum demand current ($I_L$), where,

**Figure 1:** Single-line diagram of the installation

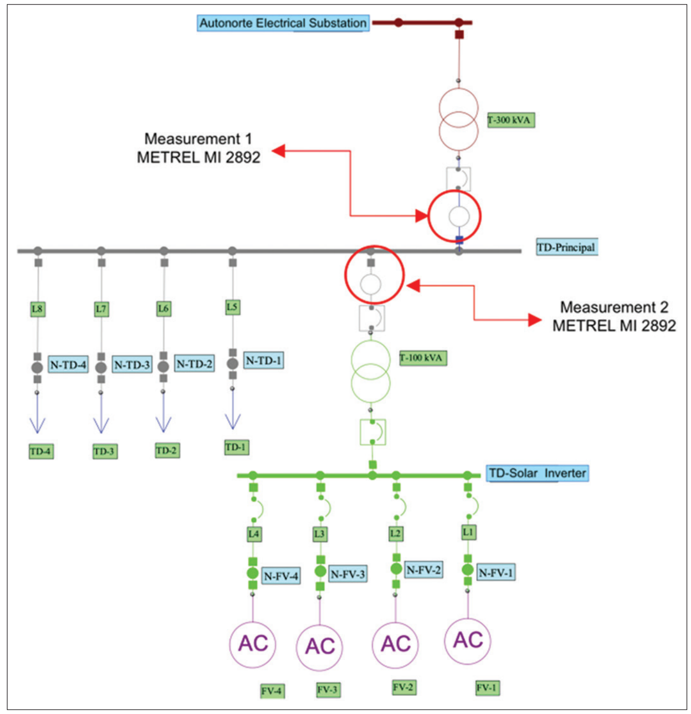



**Table 1: Current distortion limits for 120V to 69 kV systems**

| $I_{SC}/I_L$ | Individual harmonic order (odd harmonics) | | | | | |
|---|---|---|---|---|---|---|
| | $3 \leq h < 11$ | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $35 \leq h \leq 50$ | *TDD* |
| <20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

Source: *Norma Técnica Colombiana NTC 1340 - Electrotecnia. Tensiones y Frecuencia Nominales en Sistemas de Energía Eléctrica en Redes de Servicio Público*, 2013

$I_{SC}$: Short circuit current [A].
$I_L$: Maximum demand current [A].
$h$: Harmonic order.
*TDD*: Demand distortion correlation.

To calculate the relationship between the line currents and define the limits for the individual current harmonics (ICD) of the main transformer and the PV plant, the following equations are used:

$$\text{Isc}\left[\text{kA}\right] \quad \frac{I[A]}{\text{Zcc}\left[\text{pu}\right]\times 1000} \tag{1}$$

$$\text{Imax}\left[\text{kA}\right] = \max[\text{Ia};\ \text{Ib};\ \text{Ic}] \tag{2}$$

## 3. RESULTS

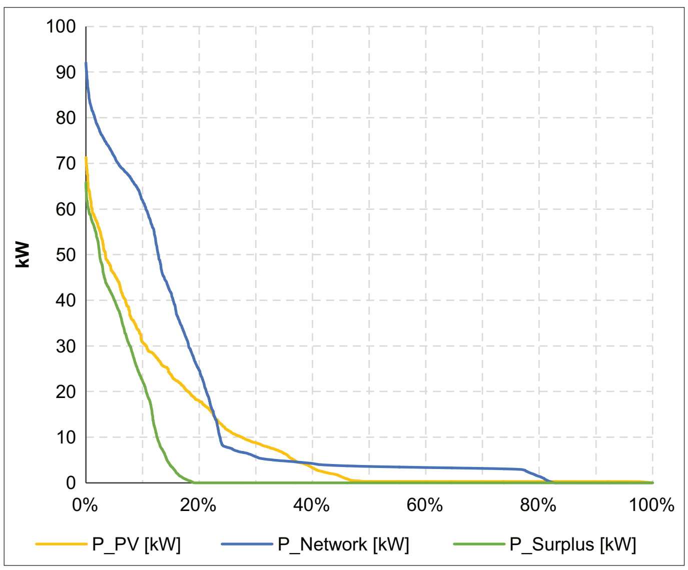
Figure 2 shows the relationship between the energy consumption of the electrical network and the PV plant in the facility under study. If the total demand for the installation is taken as a reference, between 23.90% and 76.10% of the energy required by the installation is delivered during a week. In addition, the PV plant delivers 24.87%

of surplus energy, and its generation is only higher than the grid on 6.97% of the occasions. It should be noted that the typical consumption of the electrical network occurs at night and ranges between 5 kW and 10 kW with a frequency of 56.34% of the total power demand of the network.

It is also highlighted that the surpluses of the PV plant are concentrated during the weekend, with a percentage of 83.92%. Regarding the rest of the electrical parameters, which determine the behavior of the system made up of PV energy and the electrical network, the 14 parameters presented in Tables 2 and 3, respectively, were evaluated, analyzing the upper ($L_S$) or lower permissible limits ($L_I$), the total number of data not within limits ($L_I < X > L_S$), and the minimum percentage of the sample (% $X_{min}$) for the variable not to represent a power quality problem.

In the PV plant, it is evident that the main power quality problem is the harmonics of the order 3–10, which represent a value of 16.40%, followed by the harmonics of the order 11–15, with a percentage of 4.63%, the which, despite being below 5% and not considered a power quality problem, does not leave a margin for the generation of harmonics of this order to the installation's equipment.

**Figure 2:** The combined power of the installation




In the main transformer of the installation, it was evidenced that the fundamental problem is given by the losses in the copper (PCU) with a percentage of 37.48%, and, as in the PV plant, there are harmonic problems of orders 3–10. However, the values of the K factor are 20.93% above the maximum value, leading to high losses due to eddy currents and excessive heating of the main transformer due to harmonics. The K factor is an indicator that allows estimating the capacity of a transformer to withstand the thermal effects produced by harmonic currents.

Figure 3 shows the incidence percentage of the most representative harmonics in the PV plant, where the problems in harmonics 3, 5, 11, and 13 stand out.

Figure 4 shows the incidence percentage of harmonics in the main transformer, where the problems in harmonics 3, 5, 7, 11, and 13 derived from the connection of the PV plant stand out. It is important to emphasize that in addition to the allowed limit being higher than the PV plant, the maximum percentage for harmonics of orders 1–10 is 10%. For harmonics of orders 11–17, it is 4.5%.

Figure 5 shows the correlation graph of the demand distortion (TDD) of the PV plant and the electrical network, highlighting that even when the PV generation is zero, harmonic problems occur in the installation. Since no work is done at night, the distortion corresponds to the lighting system.

Since the installation has power quality problems, correcting the losses caused by the effect of harmonics is necessary. One of the most common ways to reduce these losses is to install a passive filter at the inverter connection node of the PV plant. This device can reduce the values of the harmonic currents at the connection point of the generator at the same time as the individual harmonics

**Table 2: Evaluation of the quality of the energy in the PV plant**

| Parameter | $\bar{X}$ | σ | $L_I$ | $L_S$ | $L_I$<X > $L_S$ | $L_I$<X > $L_S$ [%] | %$X_{min}$ | Met |
|---|---|---|---|---|---|---|---|---|
| $V_L$ [V] | 221.21 | 0.99 | 202.4 | 231 | 0 | 0 | 99 | ✓ |
| VT [pu] | 1.01 | 0.005 | 0.92 | 1.05 | 0 | 0 | 99 | ✓ |
| PVU [%] | 0.36 | 0.048 | | 2 | 0 | 0. | 99 | ✓ |
| $I_L$ $I_L$ [A] | 30.04 | 36.268 | | 157 | 20 | 0.28 | 95 | ✓ |
| PCU [%] | 82.34 | 22.544 | | 30 | 0 | 0 | 95 | ✓ |
| F [Hz] | 60 | 0.019 | 59.8 | 60.2 | 0 | 0 | 95 | ✓ |
| S [kVA] | 9.22 | 14.927 | | 100 | 0 | 0 | 100 | ✓ |
| S [%] | 9.22 | 14.927 | | 100 | 0 | 0 | 100 | ✓ |
| Fp [pu] | 0.98 | 0.068 | | 0.9 | 3 | 0.04 | 95 | ✓ |
| Plt [pu] | 0.18 | 0.071 | | 1 | 0 | 0 | 95 | ✓ |
| THDV [%] | 1.18 | 0.2 | | 8 | 0 | 0 | 95 | ✓ |
| TDD [%] | 0.57 | 0.754 | | 8 | 0 | 0 | 95 | ✓ |
| IVD [%] | 0.19 | 0.29 | | 5 | 0 | 0 | 95 | ✓ |
| ICD (3–0) [%] | 4.22 | 7.498 | | 10 | 28351 | 16.4 | 95 | x |
| ICD (11–15) [%] | 0.84 | 1.484 | | 4.5 | 5004 | 4.63 | 95 | ✓ |
| Factor K [PU] | 1.81 | 0.518 | | 4 | 8 | 0.04 | 95 | ✓ |

**Table 3: Evaluation of the power quality in the main transformer**

| Parámetro | $\bar{X}$ | σ | $L_I$ | $L_S$ | $L_I$<X > $L_S$ | $L_I$<X > $L_S$ [%] | % $X_{min}$ | Cumple |
|---|---|---|---|---|---|---|---|---|
| $V_L$ [V] | 221.81 | 1.251 | 202.4 | 231 | 0 | 0 | 99 | ✓ |
| VT [pu] | 1.01 | 0.006 | 0.92 | 1.05 | 0 | 0 | 99 | ✓ |
| PVU [%] | 0.36 | 0.075 | | 2 | 1 | 0.01 | 99 | ✓ |
| $I_L$ [A] | 64.30 | 72.158 | | 787.3 | 0 | 0 | 95 | ✓ |
| PCU [%] | 92.71 | 8.704 | | 30 | 2699 | 37.48 | 95 | x |
| F [Hz] | 60 | 0.018 | 59.8 | 60.2 | 0 | 0 | 95 | ✓ |
| S [kVA] | 27.05 | 30.116 | | 300 | 0 | 0 | 100 | ✓ |
| S [%] | 9.02 | 10.039 | | 100 | 0 | 0 | 100 | ✓ |
| Fp [pu] | 0.22 | 0.351 | | 0.9 | 2159 | 29.98 | 95 | x |
| Plt [pu] | 0.21 | 0.183 | | 1 | 120 | 0.56 | 95 | ✓ |
| THDV [%] | 1.21 | 0.219 | | 8 | 0 | 0 | 95 | ✓ |
| TDD [%] | 2.08 | 1.909 | | 12 | 0 | 0 | 95 | ✓ |
| IVD [%] | 0.18 | 0.297 | | 5 | 0 | 0 | 95 | ✓ |
| ICD (3–10) [%] | 4.93 | 7.905 | | 10 | 25516 | 14.76 | 95 | x |
| ICD (11–15) [%] | 1.22 | 1.658 | | 4.5 | 3490 | 3.23 | 95 | ✓ |
| Factor K [PU] | 2.84 | 2.229 | | 4 | 4522 | 20.93 | 95 | x |

**Figure 3:** Percentage of harmonics from 3 to 15

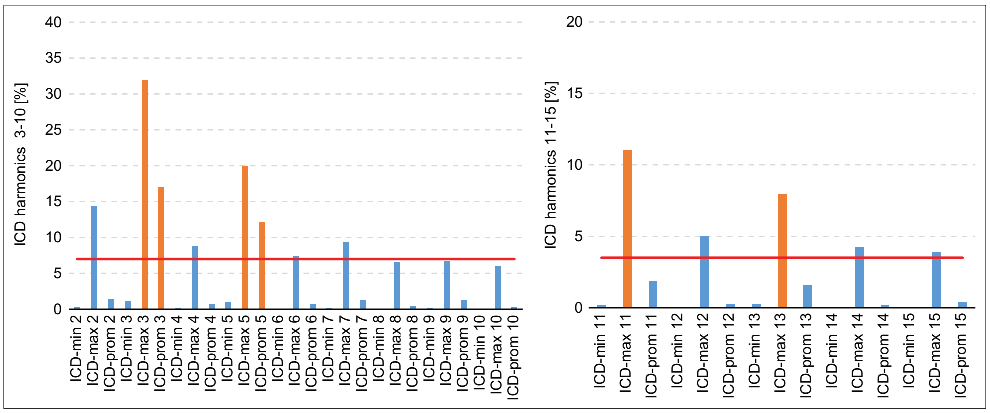
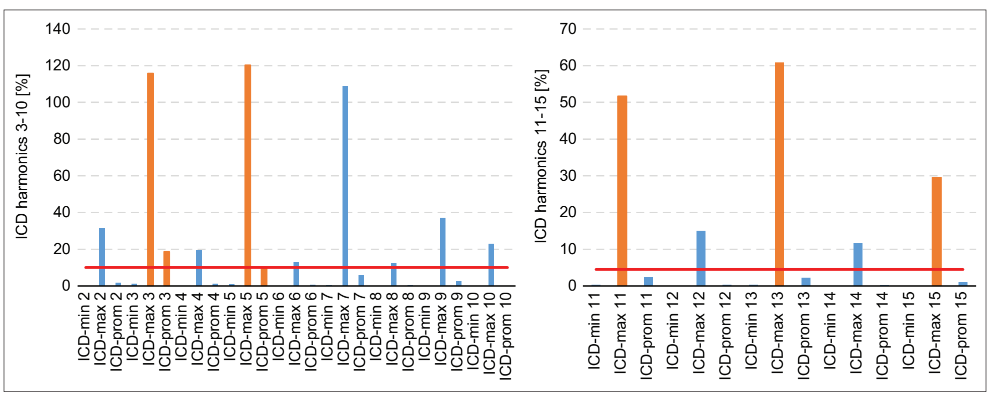



**Figure 4:** Percentage of harmonics from 3 to 15 in the main transformer




perceived at the point of connection to the electrical network are reduced. The losses due to harmonics are determined to evaluate the feasibility of performing the correction using a filter or bank of capacitors. The difference between the fundamental power ($P_{fund}$) and the total power consumed by the installation ($P_{tot}$) is given by the following expressions:

$$\sum_{t1}^{t2} P_{fund} \frac{t2-t1}{24} = E_{fund} = 680.63\,\text{kWh / day} \quad (3)$$

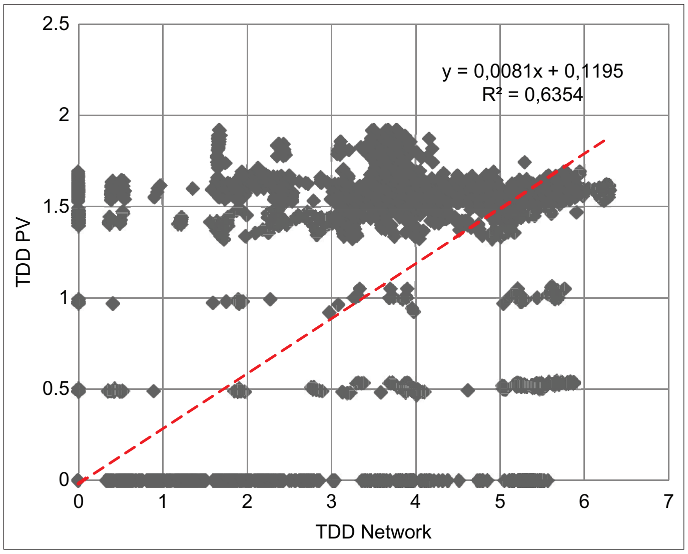
$$\sum_{t1}^{t2} P_{tot} \frac{t1-t1}{24} = E_{tot} = 682.72\,\text{kWh / day} \quad (4)$$

$$E_{losses} = E_{tot} - E_{fund} = 682.72 - 680.63 = 2.09\,\text{kWh / day} \quad (5)$$

$$Em_{losses} = E_{loses} \times 30 = 2.09 \times 30 = 62.7\,\text{kWh / day} \quad (6)$$

$$\$_{kWh} = 911.75\,\text{COP} \quad (7)$$

**Figure 5:** Correlation between the demand distortion of the photovoltaic plant and the electrical network




$$\$_{losses} = Em_{loses} \times \$_{kWh} = 62.7 \times 911.75 = 57166.725\,COP \quad (8)$$

$$\$_{losses} = 37620 \quad COP; \quad 0.31 \frac{\%}{month} \quad (9)$$

Donde:

$P_{fund}$ Power [kW]
$P_{tot}$ The total power consumed by the installation [kW]
$E_{fund}$ Energy [kWh/day]
$E_{tot}$ Energy consumed by the installation [kWh/day]
$E_{losses}$ Lost energy [kWh/day]
$Em_{losses}$ Monthly energy lost [kWh/day]
$\$_{kWh}$ Value of the kWh in Colombia [COP]
$\$_{losses}$ Value of energy losses [COP]

When evaluating the results obtained, it is determined that the losses because of harmonics are small, representing 0.31% of the monthly billing and 2.5% of the total implementation cost of the project for 25 years. However, implementing a passive filter corresponds to 6.86% of the investment cost, which makes it economically unviable and unattractive to investors.

## 4. CONCLUSIONS

Through the analysis of the data obtained by the METREL MI 2892 network analyzer, it was possible to identify that the PV plant is the primary source of generation of current harmonics of the order 3 to 10, which are reflected in the losses that exist in the main transformer of the point of connection to the local electrical network. In addition, the harmonics of orders 11–15 exceed the maximum allowable value of the K factor, generating excessive overheating of the equipment.

It should be noted that the current imbalance that exists in the main transformer corresponds to multiple single-phase loads installed on the same line. It is evident that during the installation of the PV plant, the essential loads whose consumption of the electrical network will be reduced with the incorporation of the PV plant were not balanced.

In addition, since there are problems in the power factor during the hours of most significant demand, the inverters can be used to generate capacitive reactive power. Likewise, it was shown that even though there are power quality problems in the PV systems, the losses derived from the work of these systems amount to 0.31%/month, which is not an expected value compared to the generation and cost of implementing a passive filter. This last alternative is only viable as the power of the PV system increases.

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