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Article

Efectos de sistemas fotovoltaicos en la calidad de energía y el factor de potencia en la industria, simulación y validación experimental en México

Effects of photovoltaic systems on power quality and power factor in industry, simulation and experimental validation in Mexico

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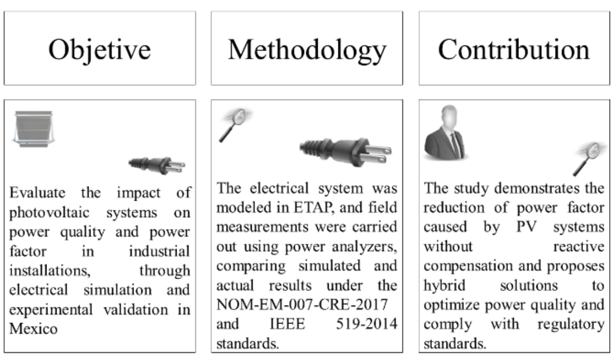
Abstract

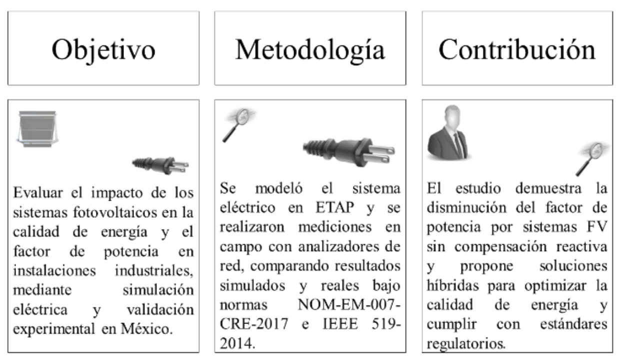
The rapid growth of photovoltaic generation in Mexico poses electrical challenges related to power factor and power quality. This study evaluates the impact of PV systems on harmonic distortion and power factor reduction in a company with critical equipment, considering the (DOF, 2017)-(CRE, 2020) and the (IEEE, 2009). Through electrical simulation and experimental measurement, losses of information and possible economic penalties were identified according to CFE data, the results show high agreement between simulations and measurements, evidencing that incorporating SFV without prior analysis can decrease the power factor and compromise stability. Hybrid and reactive compensation solutions are proposed, highlighting the importance of previous technical studies for an efficient and safe energy transition.



Photovoltaic energy, power factor, energy quality.

Resumen

El rápido crecimiento de la generación fotovoltaica en México plantea retos eléctricos relacionados con el factor de potencia y la calidad de energía. Este estudio evalúa el impacto de sistemas FV en la distorsión armónica y la reducción del factor de potencia en una empresa con equipos críticos, considerando la (DOF, 2017)-(CRE, 2020) y el (IEEE, 2009). Mediante simulación eléctrica y medición experimental, se identificaron pérdidas de información y posibles penalizaciones económicas según datos de CFE, los resultados muestran alta concordancia entre simulaciones y mediciones, evidenciando que incorporar SFV sin análisis previo puede disminuir el factor de potencia y comprometer la estabilidad. Se proponen soluciones híbridas y de compensación reactiva, resaltando la importancia de estudios técnicos previos para una transición energética eficiente y segura.



Energía fotovoltaica, factor de potencia, calidad de la energía

Area: Advocacy and attention to national problems

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Introduction

In the last decade, Mexico has experienced a remarkable growth in the adoption of photovoltaic (PV) solar energy, driven by public policies, technological advances, and the need to diversify the national energy matrix (SENER, 2024), (CENACE,2025) Electricity generation through PV systems has shown annual increases of over 25%, consolidating this technology as one of the most promising renewable energy sources in the country SENER,2024),(CENACE,2025). This progress directly contributes to fulfilling international commitments on climate change mitigation and the United Nations Sustainable Development Goals (SDGs) (IRENA, 2024).

Most PV installations in Mexico operate under grid-connected (on-grid) schemes, offering significant economic and environmental benefits. However, this model also faces technical challenges related to power quality, such as low power factor, total harmonic distortion (THD), phase imbalance, voltage fluctuations, and reactive power variations (Ahsan et al., 2021);(Li, 2018). Regulations such as (DOF, 2017) and the Grid Code 2.0 require maintaining a minimum power factor of 0.90 to avoid economic penalties, which represents a challenge for installations whose inverters lack adequate reactive compensation mechanisms (CRE, 2021).

Recent studies show that, in the absence of capacitor banks or active filters, harmonic distortion levels can exceed 10%, potentially affecting the lifespan of transformers, motors, and other sensitive loads (Hernández-Mayoral et al., 2024). In addition, research in various Latin American countries indicates that high PV penetration can cause overload losses, increase harmonics, and create current imbalance, while moderate integration with compensation strategies can improve the quality of the power supply (Anny et al., 2025);(Gandhi et al., 2020). A 160 kW PV system connected to an internal grid, associated with a 225 kVA transformer and a main 750 kVA transformer, was analyzed to evaluate power quality (HUAWEI, 2023); (FLUKE, 2012); (METREL, 2023). The analysis revealed significant problems, including a low average power factor (0.69), excessive harmonics (TDD up to 11.76%), and current imbalance (up to 77.82%), exceeding national and international standards (IEEE, 2009)

These findings highlight the need for corrective measures such as automatic capacitor banks, harmonic filters, and load balancing to ensure efficient operation and regulatory compliance.

Therefore, this study seeks to comprehensively evaluate the interaction between the PV system and the internal grid, identifying the main technical challenges and proposing solutions to improve power quality, optimize operational efficiency, and maximize the benefits of photovoltaic generation in critical environments with high demand.

Methodology

The study was carried out at the facilities of a national company located in the municipality of El Marques, Queretaro, Mexico, located at 20° 38' 54" north latitude and 100° 17' 38" west longitude, at an altitude of 1 908 meters above sea level. The area has an average annual solar radiation of 5.3 $kWh \cdot m^{-2} \cdot day^{-1}$ (SENER, 2024), a favorable condition for the use of photovoltaic energy.

The evaluated photovoltaic system has four Huawei SUN2000-40KTL-M3 inverters (40 kW each) operating at 440 Vac, connected to a 225 kVA (440/220-127 V) dry transformer, which is integrated into the 750 kVA main transformer (Delta-Star, 5.48% impedance), responsible for powering critical loads such as server systems and production equipment. The methodology used consisted of three main stages, complemented by a validation procedure:

1. Normative analysis

Existing standards and regulations were revised to define evaluation criteria and compliance limits:

- NOM-EM-007-CRE-2017: minimum power factor of 0.90.
- IEEE 519-2014: Maximum allowable total harmonic distortion (THD) of 5%.
- CFE G0100-04: Operating limits of active and reactive power.

This review made it possible to establish the technical parameters that would be used as a reference throughout the study.

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2. Modeling the electrical system

The ETAP software was used to simulate the electrical behavior before and after the photovoltaic integration, replicating the same measurement points used in the experimental monitoring to ensure direct comparability.

The model included:

- 750 kVA main transformer (Delta-Star, 5.48% impedance).
- Photovoltaic system of 160 kW nominal (360 modules).
- 225 kVA dry transformer for inverter coupling.
- Critical loads with hourly consumption profiles.
- 4 Huawei SUN2000-40KTL-M3 inverters
- Lines and internal protections of the plant.
- Critical loads (servers and production equipment).

The simulations evaluated power factor, active power, reactive power and THD in different operating scenarios:

- Normal conditions with maximum solar radiation.
- Periods of low or no photovoltaic generation.
- SFV disconnect scenarios.

3. Experimental measurement

For field measurement, three power grid analyzers were installed simultaneously for seven consecutive days, configured to record data every 20 seconds:

1. Fluke 435-II installed on the 750-kVA transformer low-voltage main board (CFE grid interconnection point).

2. Metrel MI 2892 installed in the secondary of the 225-kVA dry transformer, at the output of the photovoltaic system.

3. Metrel MI 2892 installed directly at the output of the PV inverters.

The following variables were measured at all points:

- Active power (kW).
- Reactive power (kVAr).
- Apparent power (kVA).
- Power factor (PF).
- Three-phase voltage and current.
- THD voltage and current.

The data were stored in the internal memory of the equipment for subsequent processing and comparative analysis with the simulation results.

4. Validation procedure

The results obtained in DWTP were contrasted with the experimentally measured data, verifying the coherence between both sources and evaluating the discrepancies. This process made it possible to quantify the real impact of the photovoltaic system on the power factor and power quality, as well as to identify the contribution of inductive loads to the deterioration of electrical indicators in periods of low or no solar generation.

Results

The simulated results were verified with the measured data to validate the behavior and determine the real magnitude of the electrical affectation due to the installed photovoltaic system which covers approximately 75% of the consumption of the place, the active power was approximately 5.69 kW, while the reactive power was -23.3 kVAr according to the simulation carried out in ETAP(Figure 1). These data allowed us to determine an approximate power factor of 0.237, according to the formula described below:

$$Fp = \frac{P}{\sqrt{P^2+Q^2}}$$

where:

P is the active power in Watts
Q is the reactive power Var
FP is the power factor (dimensionless)

Then:

$$0.237 = \frac{5.69k}{\sqrt{(5.69k)^2+(-23.3k)^2}}$$

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The values obtained in the simulation (Figure 1) show a significant decrease with respect to the minimum thresholds established by national regulations (NOM-EM-007-CRE-2017) and international standards (IEEE 519-2014), so the results indicate a high prevalence of negative inductive reactive power from the inverter when the photovoltaic modules and the T2 are connected to the electricity grid. which could generate economic penalties and a decrease in energy efficiency due to the low power factor that is generated, on the other hand when disconnecting the photovoltaic system in the ETAP simulation software – specifically the T2 transformer (Figure 2) – a notable change was observed in the power triangle, with a significant improvement in the power factor, reaching a value of 0.985 when applying the data in the corresponding formula.

Box 1

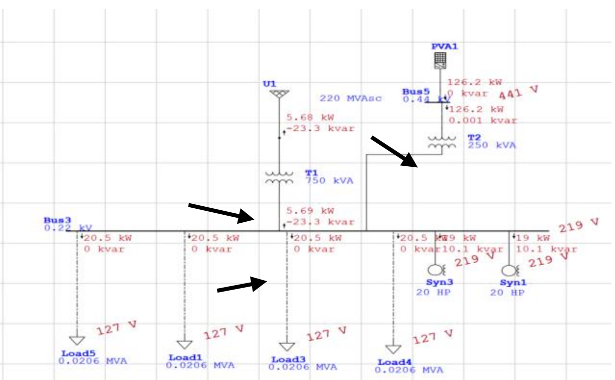

Figure 1

Simulation of a photovoltaic system interconnected to the grid

Source Generated using ETAP

Box 2

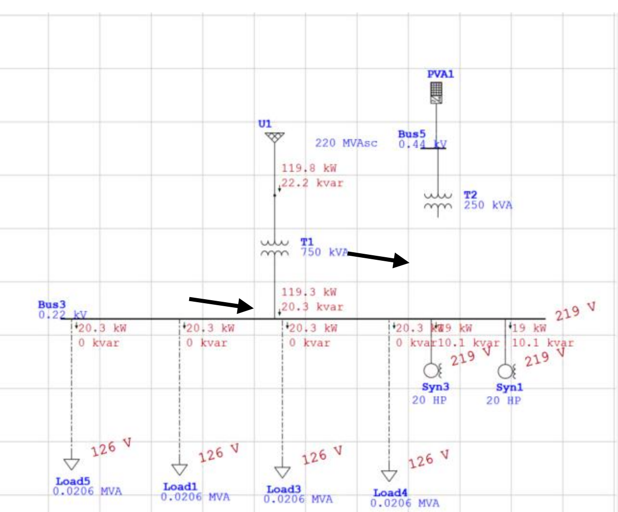

Figure 2

Simulation of electrical system with FP at 0.985 and transformer disconnected

Source Generated using ETAP

These results coincide with the historical records of the CFE before and after the installation of the photovoltaic modules, where it is observed that the FP starts is 97.81% in June 2024, which indicates a well-compensated electrical system, while as of July, the FP falls to 86.09% and in August-September it reaches 79.44% just one month after the photovoltaic system (PVS) was installed, reflecting an increase in the demand for reactive power, in November 2024, the FP rises to 85.36%. In December 2024 (80.51%), with the PV system already in operation, there is no evidence of a clear improvement in the FP.

This suggests that investors are injecting active power, but not reactive offset. In the month of January, FP reached 89.44%. The PF was reduced after June 2024, reflecting an increase in reactive power due to the fact that PV inverters only generate real power (kW) and not reactive power (kVAR). As it does not produce reagents, the demand for this power continues to depend on the CFE grid, which keeps the reactive power consumed constant while the actual power injected by the photovoltaic system increases.

This imbalance increases the angle of the power triangle, which in turn decreases the power factor. In graphic terms, when the base of the triangle is reduced (real power) and the height (reactive power) is maintained, the relationship between the two causes a worsening of the power factor, generating lower values, this decrease in PF is due to the fact that photovoltaic inverters only generate active power (kW) and not reactive power (kVAr). As it does not produce reagents, the demand for this power continues to depend on the CFE network, keeping the reactive power consumed constant while the actual power injected by the PV system increases.

This imbalance increases the angle of the power triangle, reducing the ratio of active to reactive power, and worsening the power factor. To support these findings, the results of the measurements made in the main low-voltage panel of the 750 kVA T1 transformer (13200 V primary / 220/127 V secondary) are presented, where the variation of Phase to Neutral Voltage and the voltages between phases show a stable trend, consistent with the system configuration. However, abrupt voltage drops were recorded at specific times, indicating possible transient events, network failures or momentary disconnections. (Figure 3).

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Box 3

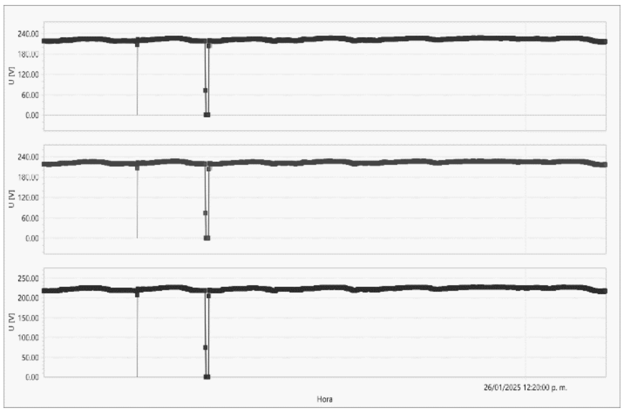

Figure 3
Voltage Variation Between Phases
Source Generated using Power Quality Analyser

Although the voltages do not present visible problems, as shown in Figure 3, it is observed that it complies with the provisions of IEEE STD 1159-2009, on the other hand, the study distinguishes a particular behavior in the power triangle of the 750 kVA T1 transformer (13200 V primary / 220/127 V secondary) due to the fact that the active power (kW) shows a cyclical pattern, with peaks during the day and reduced values at night, reflecting the interaction between the grid and solar generation (Figure 4).

Box 4

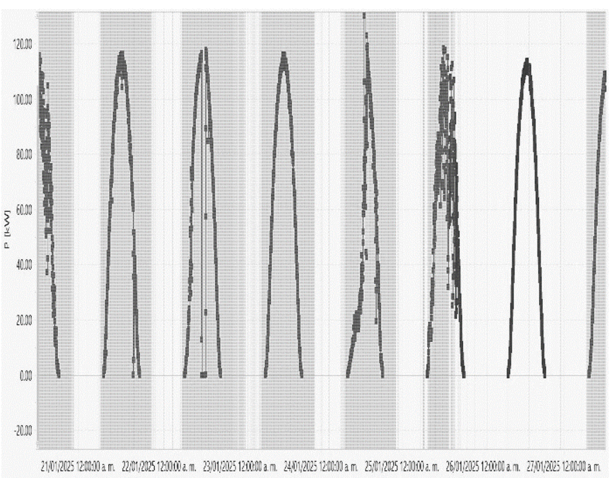

Figura 4
Variation in active power
Source Generated using Power Quality Analyser

On the other hand, the reactive power (kVAr) presents maximums during the day and decreases near zero at night, which indicates the operation of inductive loads and the partial compensation of the photovoltaic inverters, as a consequence of these variations, the apparent power (kVA) exhibits a cyclical behavior with daily peaks of up to 120 kVA, reflecting total demand (Figure 5)

Box 5

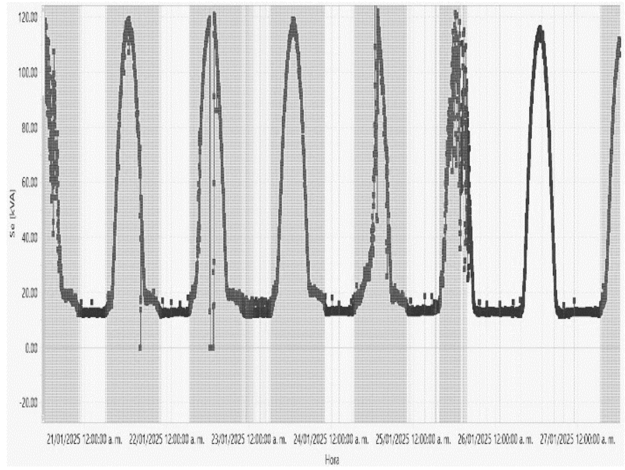

Figure 5
Apparent power variation
Source Generated using Power Quality Analyser

So a particular behavior is confirmed in the power triangle, directly affecting the PF that varies clearly between day and night, reaching values close to 1.0 during PV generation and decreasing outside that period, this indicates that the photovoltaic system does not improve the PF while operating, since the PF falls below 0.9 as the production of photovoltaic energy increases, regularizing the PF when there is little energy produced by the panels (Figure 6).

Box 6

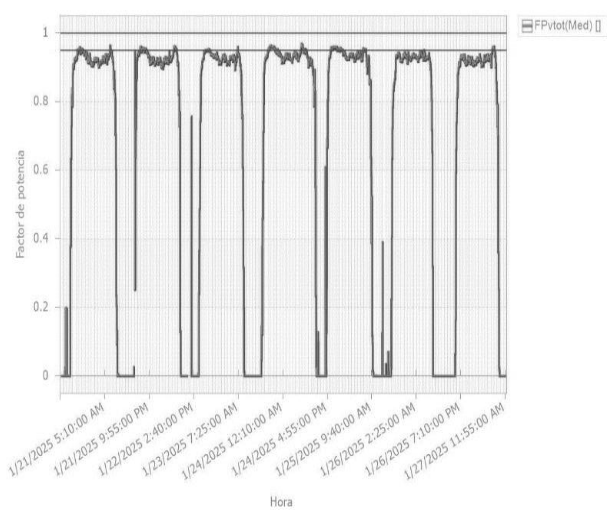

Figure 6
Power factor variation
Source Generated using Power Quality Analyser

Regarding the results of the network analyzers connected to the solar panel panel, it was found that the currents in phases A, B and C show a daily cyclical pattern with peaks greater than 200 A, reflecting the fluctuating demand of load and the start-up of transient equipment,

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these variations show the influence of photovoltaic generation and the changes in the connected load with respect to the potencias, la activa sigue un diurnal behavior with peaks of up to 104.8 kW, while reactive behavior varies between 15 and 30 kVAr, presenting at times values close to zero or even negative, which indicates a partial compensation of reagents by investors (Figures 7).

Box 7

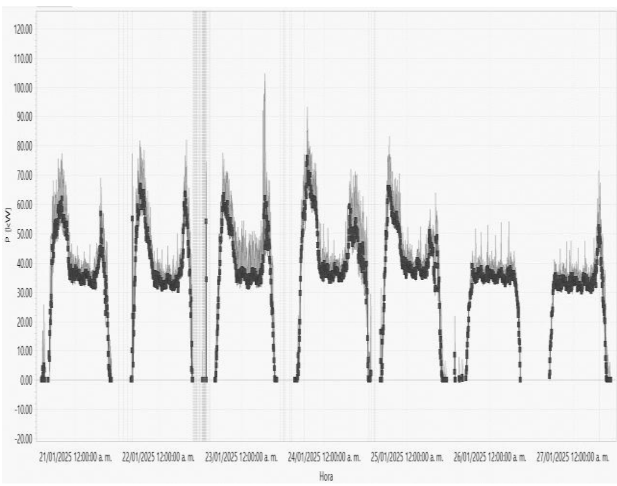

Figure 7

Active power variation in the photovoltaic system

Source Generated using Power Quality Analyser

The apparent power reaches up to 151.5 kVA, clearly showing the interaction between photovoltaic generation and energy demand (Figure 8). The power factor, on the other hand, presents high variability, with periods below the regulatory threshold of 0.9, reflecting fluctuations in the demand for reactive power and insufficient compensation from investors at certain times. In addition, current harmonics were recorded above the established limits, with a TDD of up to 11.76%, in breach of the RED 2.0 regulation. and a current imbalance that reached up to 77.82%, also outside the permitted limits.

Box

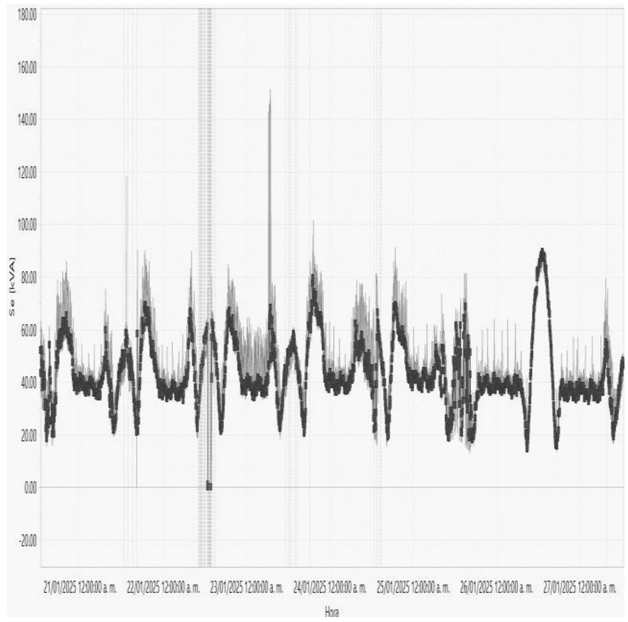

Figure 8

Apparent power variation in the photovoltaic system

Source Generated using Power Quality Analyser

Conclusions

The power quality analysis carried out revealed three problems that compromise the efficiency and reliability of a photovoltaic system (PVS) and the internal grid. First, the power factor presented an average of 0.69, a value significantly lower than the regulatory minimum of 0.90, which generates inefficiencies and cost overruns in electricity billing. Secondly, an excess of harmonics was identified, particularly in orders 3 and 5, failing to comply with the standards established in the Network Code and affecting the quality of the electricity supply. Finally, a current imbalance of more than 15% was observed, a situation that can cause overheating and reduce the useful life of transformers and critical equipment.

Declarations

Conflict of interest

The authors declare that there is no conflict of interest. They have no known competitive financial interests or personal relationships that could have influenced the work reported in this article.

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The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

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Authors' contribution

Tellez-Hernández, Felipe: Conceptualization of research, development of simulations in DWTP, data collection with power quality analyzers, writing of the original draft and validation of results.

Pineda-Piñón, Jorge: Supervision of the experimental stage, guide in the application of international standards (IEEE 519-2014, IEEE 1547-2018, NOM-EM-007-CRE-2017) and critical review of the methodology.

Sánchez-Vega, Guadalupe O.: Contributed to data analysis, measurement processing of the Fluke 435-II and Metrel MI 2892 equipment, preparation of tables and figures.

Mota-Del Carpio, Jimena: Supported the experimental stage, assisting in equipment configuration, field data acquisition, and verification of system performance.

Availability of data and materials

The datasets generated and/or analyzed during this study are available upon request from the corresponding author. The raw measurement files of the Fluke 435-II and Metrel MI 2892 analyzers, as well as the ETAP simulation files, have been archived and can be shared for academic purposes.

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Abbreviations

FP – Power Factor
CFE - Federal Electricity Commission
FP - Power Factor
kVA - Kilovolt-ampereo
kVAr - Reactive Kilovolt-ampere
kW – Kilowatt
PV – Photovoltaic
PVGIS - Photovoltaic Geographic Information System
SFV - Photovoltaic System
THD - Total Harmonic Distortion

References

Antecedents

Anny, H. R., Agustin, I. R., & Ricardo, C. H. (2025). Increasing photovoltaic hosting capacity in distribution networks in Puerto Rico: Seasonal and technical characteristics analysis and solutions. *Energy Reports*, *14*, 867–885.

CENACE. (2025). *Centro Nacional de Control de Energia Estadistica de la Energia Generada Liquidada Agregada (MWh) Intermitente y Firme por Tipo de Tecnologia*.

Gandhi, O., Kumar, D. S., Rodríguez-Gallegos, C. D., & Srinivasan, D. (2020). Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration. *Solar Energy*, *210*, 181–201.

IRENA. (2024). *World Energy Transitions Outlook 2024: 1.5°C pathway*.

Li, C. (2018). Comparative performance analysis of grid-connected PV power systems with different PV technologies in the hot summer and cold winter zone. *International Journal of Photoenergy*, *2018*.

SENER. (2024). *Programa Sectorial de Energía 2020-2024.*

Basics

CRE. (2020). *NOM-001-CRE/SCFI-2019.*

CRE. (2021). *MANUAL DE REQUERIMIENTOS TÉCNICOS PARA LA INTERCONEXIÓN DE CENTRALES ELÉCTRICAS AL SISTEMA ELÉCTRICO NACIONAL 2 CONTENIDO.*

DOF. (2017). NOM-EM-007-CRE-2017. *DOF.*

FLUKE. (2012). *Fluke 4 3 4 -II/435-II/437-II Analizador trifásico de energía y calidad de la energía eléctrica*.

HUAWEI. (2023). *Efficiency Curve Circuit Diagram Reliable Smart Safe.*

IEEE. (2009). *Monitoring Electric Power Quality maquinas electricas fime (Escuela Superior de Ingeniería Mecánica y Eléctrica Unidad Culhuacan).*

METREL. (2023). *Analizadores de calidad de energía MI 2892 Power Master*.

Supports

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 (Switzerland)*, *13*(7).

Hernández-Mayoral, E., Jiménez-Román, C. R., Enriquez-Santiago, J. A., López-López, A., González-Domínguez, R. A., Ramírez-Torres, J. A., Rodríguez-Romero, J. D., & Jaramillo, O. A. (2024). Power Quality Analysis of a Microgrid-Based on Renewable Energy Sources: A Simulation-Based Approach. *Computation*, *12*(11).

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