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Evaluation of Power Quality in a 62.4 kW PV Grid-Connected System in Libya

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Grid-connected photovoltaic, Power Quality, iTHD , vTHD, harmonic, Solar irradiance.

ABSTRACT

This paper conducts a comprehensive analysis of Power Quality (PQ) variations correlated with solar irradiance, emphasizing their significance in a 62.4 kWp PV grid-connected system. Installed in 2021 at the Libyan Center for Solar Energy Research and Studies (LCSERS) in Tajura, Libya (Latitude 32.81°N, Longitude 13.43°E), the system features a 50 kW SMA Core One inverter and serves as a car park. Given the inherent instability in Libya's public network, a thorough examination of the impact of these systems becomes imperative.

The primary focus of this study is the critical analysis of PQ parameters, encompassing voltage, current, frequency, active and reactive power, power factor, harmonics distortion, and solar irradiance variations. The analysis is further compared with international standards, such as Institute of Electrical and Electronics Engineers (IEEE). The findings reveal a substantial correlation between PQ variations and PV power output, presenting a potential series threat to future distribution networks.

This paper offers valuable insights into understanding the implications of Power Quality variations in photovoltaic systems, particularly in regions with unstable public networks. The identified strong relationship between PQ variations and PV power output underscores the necessity of addressing these issues for the sustainable integration of solar energy into distribution networks.

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تقييم جودة الطاقة في نظام طاقة شمسية متصل بالشبكة بقدرة ٦٢,٤ كيلوواط في ليبيا

عبدالرزاق لبز, ميلاد بشيري, الشيباني المرابط, ناجية الحاتمي , فيصل ازريق , توفيق البوعيشي.

ملخص: يُجري هذا البحث تحليلاً شاملاً لتغيرات جودة الطاقة (PQ) المرتبطة بالإشعاع الشمسي، مع التأكيد على أهميتها في نظام طاقة شمسية متصل بالشبكة بقدرة 62.4 كيلوواط. تم تركيب هذا النظام في عام 2021 في المركز الليبي لأبحاث ودراسات الطاقة الشمسية (LCSERS) في تاجوراء، ليبيا (خط العرض 32.81° شمالاً، خط الطول 13.43° شرقًا)، ويتميز بوجود عاكس SMA Core One بقدرة 50 كيلوواط، كما أنه يستخدم كموقف للسيارات. نظرًا لعدم استقرار الشبكة العامة في ليبيا، يصبح من الضروري إجراء دراسة دقيقة لتأثير هذه الأنظمة.

يركز هذا البحث بشكل أساسي على التحليل النقدي لمتغيرات جودة الطاقة، والتي تشمل الجهد، التيار، التردد، القدرة الفعالة وغير الفعالة، معامل القدرة، التشوهات التوافقية، وتغيرات الإشعاع الشمسي. كما تتم مقارنة النتائج بالمعايير الدولية مثل معايير معهد مهندسي الكهرباء والإلكترونيات (IEEE).

تكشف النتائج عن وجود ارتباط كبير بين تغيرات جودة الطاقة وإنتاج الطاقة الشمسية، مما يمثل تهديدًا محتملاً لشبكات التوزيع المستقبلية. يقدم هذا البحث رؤى مهمة لفهم تأثير تغيرات جودة الطاقة في أنظمة الطاقة الشمسية، خاصة في المناطق التي تعاني من عدم استقرار الشبكات العامة. كما أن العلاقة القوية التي تم تحديدها بين هذه التغيرات وإنتاج الطاقة الشمسية تؤكد الحاجة إلى معالجة هذه القضايا لضمان دمج مستدام للطاقة الشمسية في شبكات التوزيع.

الكلمات المفتاحية – أنظمة كهروضوئية متصلة بالشبكة، جودة الطاقة، التشوه التوافقي الكلي للتيار (iTHD)، التشوه التوافقي الكلي للجهد (vTHD)، التوافقيات، الإشعاع الشمسي.

1. INTRODUCTION

Libya, situated in North Africa, spans an expansive 1,759,540 km² and boasts a 1900 km-long coast [1]. Positioned as a significant nation in the Mediterranean basin, Libya stands out as the wealthiest in North Africa concerning natural resources. Recent times have witnessed Libya emerge as one of the world's primary energy sources, being the largest exporter of natural gas and oil [2]. However, amidst its energy wealth, Libya faces environmental challenges, rapid demand growth, and high energy consumption, resulting in power interruptions.

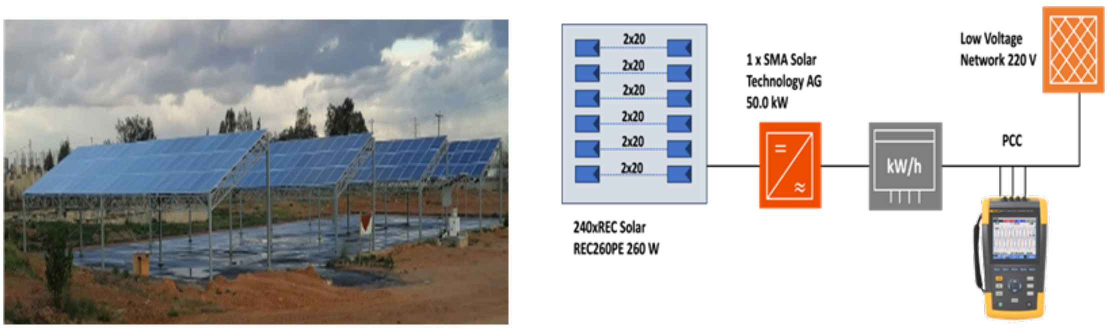
The country's economic backbone relies heavily on oil, making oil and gas products the predominant sources of power generation [3][4]. Consequently, the exploration of alternative energy sources, such as wind and solar, emerges as a viable solution to reduce reliance on fossil fuels and mitigate carbon dioxide emissions. Libya stands as a country abundant in renewable energy resources, specifically wind and solar energy [5]. The annual average of PV power varies from 1753 kWh/ kWp in certain coastal regions to 2045 kWh/ kWp in the southern areas, as depicted in the solar atlas maps. Moreover, the average annual sunshine duration extends from 3100 to 3900 hours [6] [7]. These findings highlight the favorable conditions for harnessing solar energy in Libya, further emphasizing the potential for reducing reliance on traditional energy sources and curbing carbon emissions [8].

In this regard, Libya possesses abundant solar energy resources, owing to its strategic location in the heart of North Africa. With a vast territory spanning 1,759,540 km^2 and a lengthy coastline of 1900 km along the Mediterranean Sea, a significant portion of approximately 88% of its landmass comprises desert regions. These desert areas exhibit immense potential for harnessing solar and wind energy, making them ideal for electricity generation through various conversion methods such as thermal, photovoltaic, and solar energy technologies. Exploiting these renewable energy sources can contribute significantly to Libya's sustainable development and energy independence [9] [10].

This paper aims to introduce and assess measurements derived from power quality metrics gathered at the photovoltaic (PV) site. The evaluated power quality parameters encompass complex, active, and reactive power, as well as current and voltage harmonics, along with power factors. Additionally, the harmonic distortion in voltage and current has been quantified for two specific days, specifically, July 28, 2023, and August 11, 2023, chosen as illustrative examples of predominantly “sunny” conditions. Sometimes, the power factor has been observed to surpass acceptable limits, resulting in the delivery of significant amounts of reactive power to the distribution network.

2. DESCRIPTION OF THE PHOTOVOLTAIC SYSTEM

The PV power plant under this study was installed as a car park, located in Tajura, at Libyan Center for Solar Energy Research and Studies, Tripoli, Libya. This system was installed at the end of 2021. After completing one year and a half of study we will be able to assess and confirm the real conditions of the PV Grid-connected system as in Figure 1a ,and Figure 1 b shown single line diagram the Layout of the connection setup.



(a) **(b)**

Figure 1. (a) Installed in LCSERS is a 62.4 kW peak PV carpark system. (b) shows the layout of the connection setup.

3. METHODOLOGY

Extensive data on power quality parameters were meticulously collected at the inverter output side substation, also known as the Point of Common Coupling (PCC). A Fluke 435-II power quality analyzer Fig. 2 was employed for the data collection process. This analysis covered two distinct periods: the initial phase from 27/7/2023 to 2/8/2023 and the subsequent period from 9/8/2023 to 13/8/2023. These time frames correspond to the commencement of the first part of a year-and-a-half-long project, with a specific focus on monitoring the summer season as detailed in this paper.

The monitoring involved a comprehensive examination of Power Quality parameters, including voltage (V), current (I), power factor (PF), active power (P), reactive power (Q), reactive power (S), harmonics, flicker, unbalance, sags, and swells for the PV system connected to the network. Additionally, meteorological and electrical output data were gathered and monitored using SMA inverter software. This thorough data collection initiative is an integral component of the ongoing project, contributing to the understanding of power quality dynamics (Power Factor, Voltage Fluctuations, Harmonics, Transient, and Frequency Variations) during the summer season within the context of photovoltaic system integration.

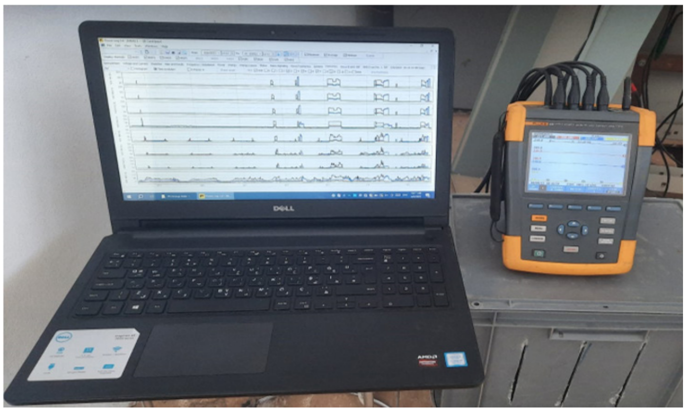


Figure 2. Power quality analyzer.

The PQ Fluke-435II analyzer was connected to the 380 V side of the nearby substation (11kV/380V), which is fed by the PV system through a three-phase, four-wire cable. The cable has a length of 100 m, a cross-section of 75 mm, and specific electrical characteristics, including Resistance AC per meter AC (0.1918 Ω/m at 20 oC) and impedance (0.2862 Ω/m), which are crucial for accurate power quality measurements.

4. RESULTS AND DISCUSSION

4.1. Model Suggested for Power quality

Power quality parameters from the output of the installed PV system at the Point of Common Coupling (PCC) were meticulously monitored and correlated with solar irradiance data obtained from the same site. Given the diverse variations in the monitored power quality parameters, this paper focuses its analysis on the most crucial aspects: voltage, current, frequency, active and reactive power, power factor, and harmonics distortion. The analysis concentrates in two specific days, namely 28/7/2023 and 11/08/2023, selected as representative instances of predominantly "sunny" days. These days were extracted from the two weeks of measured data, aligning with corresponding solar irradiance measurements. This selective approach provides a more nuanced understanding of the system's behavior under optimal solar conditions, contributing to a comprehensive assessment of the PV system's performance.

The study investigated the relationship between the variation of output voltage and current Figur 3 at the Point of Common Coupling (PCC) concerning solar irradiance. The findings indicated no substantial difference in the magnitude of phase voltage variation within the range of 3 to 7 V for both days, with phase C exhibiting a slightly larger value. Importantly, due to these variations, the recorded voltage unbalance ranged between 0.20% and 1.60% as maximum value. These variations of phase voltage remained well within the international limits at the PCC, irrespective of varying solar irradiance levels, and the voltage unbalance was maintained within the international standard limits.

Conversely, the current variations demonstrated a clear correlation with changes in solar irradiance during the selected days under study. Despite this, the study concludes that the rate of irradiance change has no significant impact on voltage fluctuation at the PCC and significant impact on output current, highlighting the system's resilience to solar irradiance fluctuations.

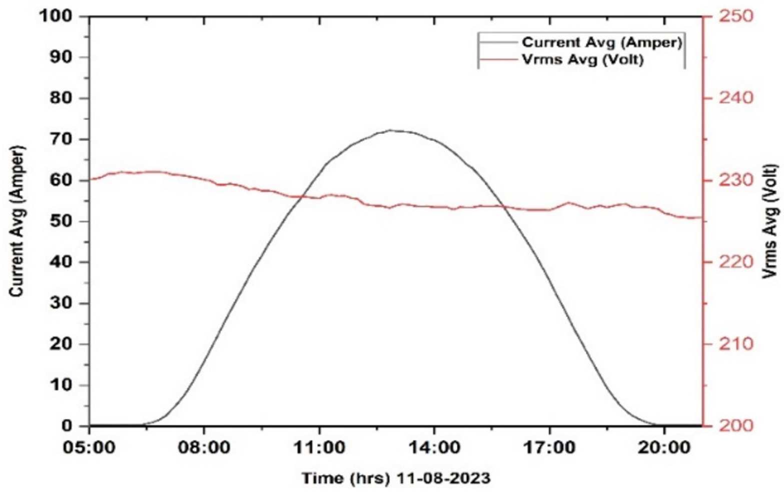


Figure 3. Variation of voltage and current vs time (11-08-2023).

The frequency variation at the Point of Common Coupling (PCC) of the studied PV system is depicted in Figure 4, clearly indicating that the frequency variation remains within the range of 49.7 Hz to 50.3 Hz. These values comply with the international PV grid requirements for normal operating frequency variations, underscoring the system's adherence to established standards. The observed frequency range suggests a stable and well-regulated operation of the PV system in terms of frequency, meeting the specified international norms.

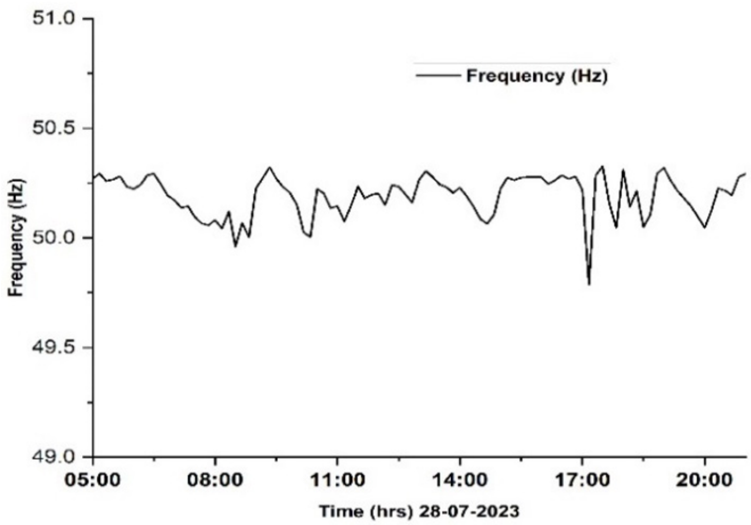


Figure 4. Frequency variation of PV system (28-07-2023).

Figure 5 illustrates the variation of reactive power correlated with solar irradiance. The fluctuations commence at sunrise, reaching a total average value near 90 Vars, and conclude at sunset with a total average value of around 50 Vars. Notably, at 13:30 for both selected days under study, there is a power total peak value within the range of 225 Vars. This pattern highlights the dynamic response of reactive power to solar irradiances throughout the day, with significant variations observed during specific time intervals.

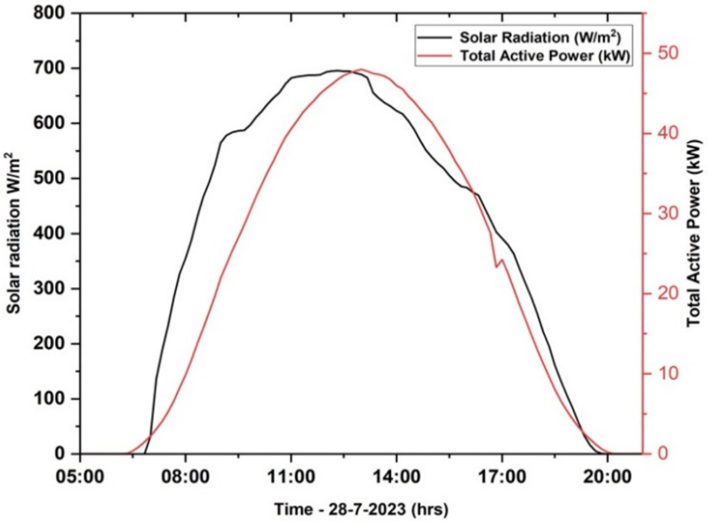


Figure 5. Reactive Power vs Solar irradiance (28-07-2023).

The correlation between the variation of generated active power and solar irradiance for the two selected days, representing clear summer conditions, is illustrated in Figure s. 6&7. The graphs distinctly portray that the inverter delivers active power of lower quality during periods of low solar irradiance and achieves maximum output when exposed to high solar irradiance. During instances of reduced and varying solar irradiance, both the PV output power and the corresponding inverter input power undergo notable changes and remain relatively low. Operating under such conditions, the inverter exhibits substantial nonlinearity due to the low input power. This observation underscores the impact of solar irradiance levels on both the quality and magnitude of the active power supplied by the inverter.

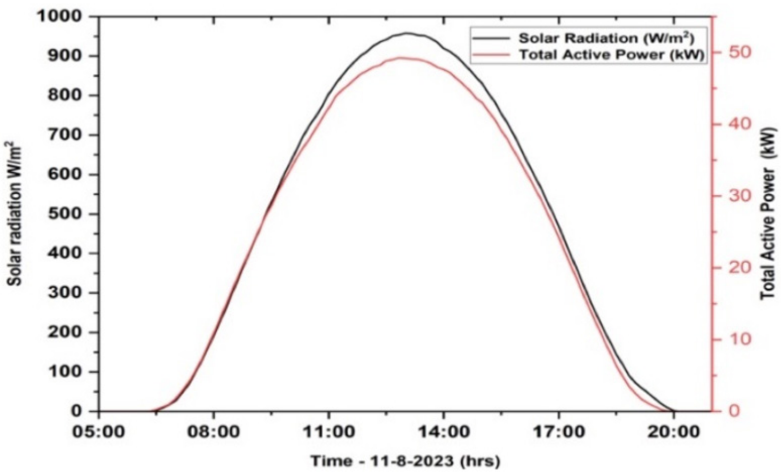


Figure 6. Active Power vs Solar irradiance (28-07-2023).

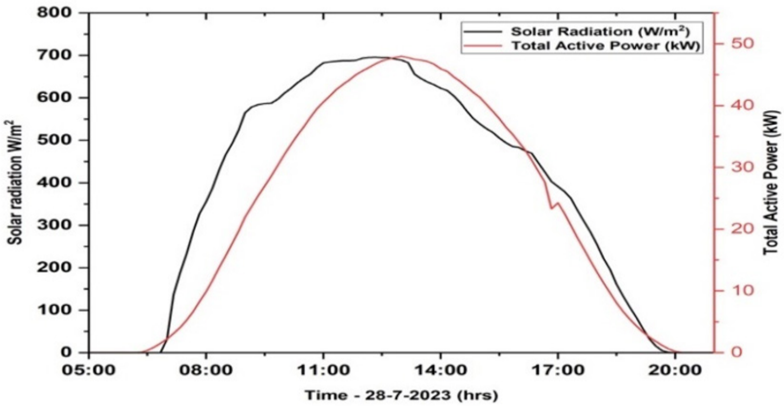


Figure 7. Active Power vs Solar irradiance (11-8-2023).

In Figures.8&9, the dependence of the PV grid-connected system's Power Factor (PF) on solar irradiance is depicted. It is evident that a decrease in PF value is observed during periods of low irradiance, particularly in the early morning before complete sunrise and before complete sunset. While high solar irradiance intensities are more conducive to obtaining a high-power factor and efficiency from PV panels, it is noteworthy that grid-connected PV systems do not consistently operate at maximum power. The observed variation in PF emphasizes the influence of solar irradiance levels on the power factor dynamics of the PV system, highlighting the nuanced response of the system to changing environmental conditions. The graphs illustrates a clear dependency of the Power Factor (PF) of the PV grid system on solar irradiance intensity, given the continuous changes throughout the day and occasional attainment of unity PF. On the inverter output side, during periods of low solar irradiance, the phase angle between voltage and current increases, resulting in a smaller PF. Consequently, at low PV output power, the inverter operates as a nonlinear load. It is desirable for the PF to be as close as possible to unity in a PV system, underscoring the importance of optimizing power factor performance for enhanced system efficiency and stability.

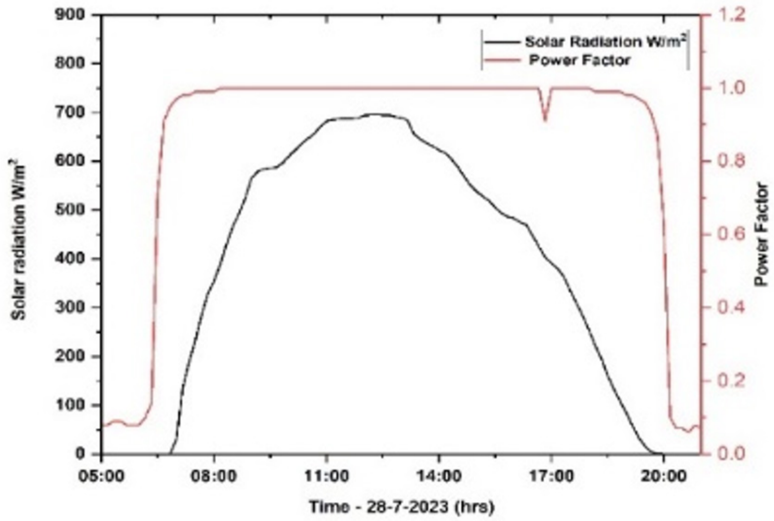


Figure 8. Power factor vs Solar irradiance (28-7-2023).

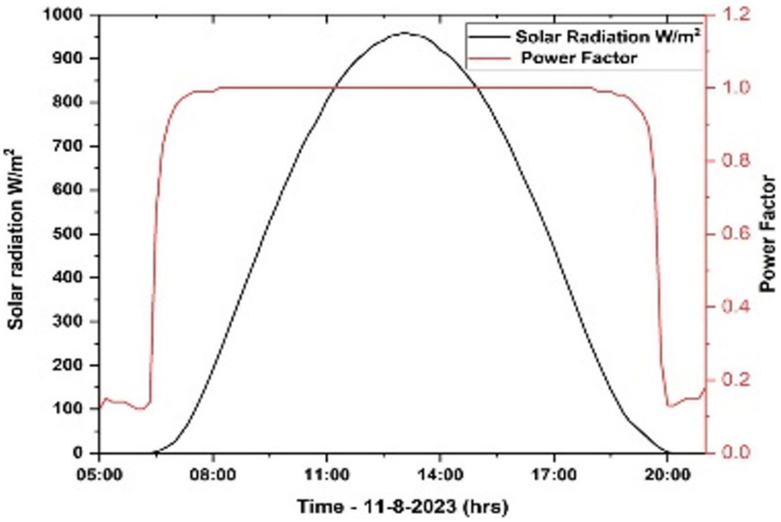


Figure 9. Power factor vs Solar irradiance (11-8-2023).

4.2. ITHD &VTHD analysis

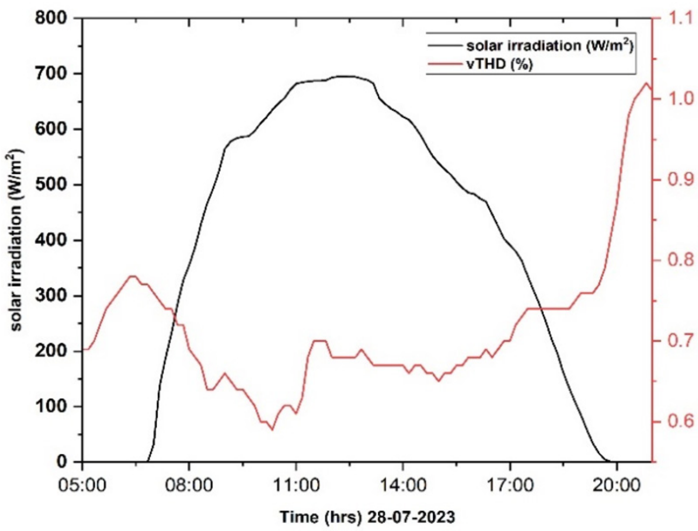


Figure 10. Solar Irradiance vs vTHD (28-7-2023).

A correlation between solar irradiance and total harmonic distortion of both voltage and current (vTHD & iTHD) was conducted. The investigation of vTHD parameters, as depicted in Figure 9, indicates that during the selected days, it remained consistently non-significant and unaffected by the variations in solar irradiance. The values of vTHD were observed to range between 0.8% and 1.60%, emphasizing the stability of the vTHD parameters during the specified period. The voltage total harmonic distortions (vTHD) during a clear sunny day are within acceptable limits. Figures. 11&12 illustrates the variations in iTHD (total harmonic distortion of current) alongside solar irradiance changes during the studied days. It is evident from the graph that significant high values of harmonic distortion are produced during periods of low solar irradiance. It is imperative for iTHD values to align with the specifications outlined by international standards to ensure improved Power Quality (PQ) in grid-connected PV systems. The observed correlation between solar irradiance and iTHD underscores the importance of monitoring and maintaining harmonic distortion within established limits for optimal system performance.

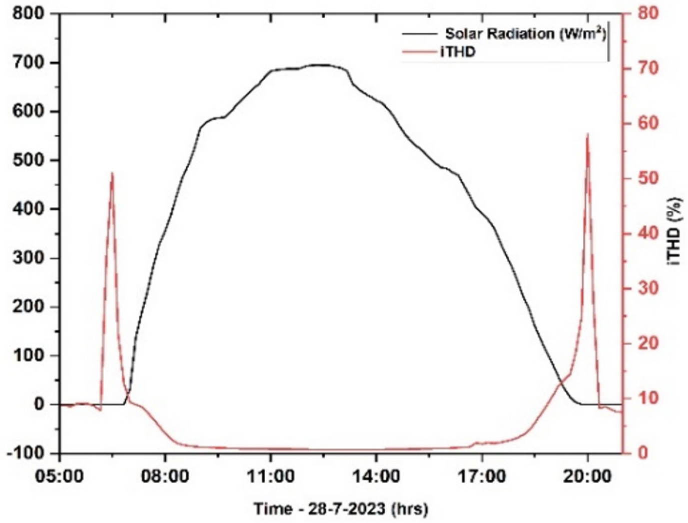


Figure. 11. Solar Irradiance vs iTHD (28-7-2023).

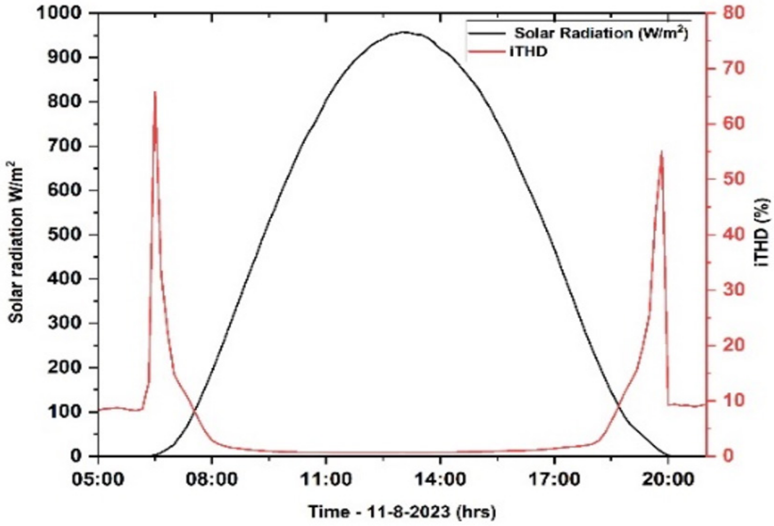


Figure 12. Solar Irradiance vs iTHD (11-8-2023).

The iTHD values before sunrise and sunset, as well as during PV operation (between sunrise and sunset), are shown in Table 1 below. Additionally, the iTHD values at sunrise and sunset are presented in Table 2 below.

Table1. ITHD Before sunrise and sunset, During PV operation.

Phases	% iTHD for (28 / 7) & (11/8)	
	Before Sun Rise & Sun Set	During PV operation
A	9.0 ~ 7.0	0.60 ~ 4.0
B	36.0 ~ 11.0	0.50 ~ 4.0
C	19.0 ~ 9.0	0.60 ~ 5.0

Table2. ITHD Before sunrise and sunset, During PV operation.

Phases	% iTHD for (28 / 7) & (11/8)	
	At Sun Rise	At Sun Set
A	50.0 ~ 65.0	55.0 ~ 60.0
B	40.0 ~ 80.0	45.0 ~ 80.0
C	50.0 ~ 80.0	50.0 ~ 70.0

It is clear that the system injects highly distorted current with respect to the fundamental frequency to the distribution network during low solar irradiance conditions. The result confirms high harmonic content distortion (iTHD) above the standard acceptable limits. The iTHD impact can be more substantial for a sudden drop of solar output power from high solar irradiance PV plant, In the case of a large PV system connected to the grid this requires some mitigation to decrease Harmonic distortion.

5. CONCLUSION

This paper conducts a comprehensive analysis of some Power Quality (PQ) variations correlated with solar radiation, emphasizing their significance in a 62.4 kWp PV grid-connected system. The impact of solar irradiance on frequency, voltage, current, active and reactive power, as well as harmonic distortion of voltage and current, has been investigated. Frequency variation at the Point of Common Coupling (PCC) comply with the international PV grid requirements for normal operating frequency variation. Phase voltage variations and unbalance remained well within the international limits at the PCC, irrespective of varying solar irradiance levels. In contrast the current variations demonstrated a clear correlation with changes in solar irradiance. The active power delivered to the distribution network has been found to vary linearly with changes of the solar irradiance incident on the PV modules. The reactive power produced have low dependence on solar irradiance at low solar irradiance. It has been observed that low solar irradiance significantly affects the power quality of the PV system's output. The most notable effect of solar irradiance is on the iTHD values, which can reach high levels, ranging from 60% to 80%, particularly during the morning and evening, especially during sunrise and sunset when solar irradiance is low. The iTHD reaches its steady state value of 0.5% - 5% when the solar irradiance value is more than 750 W/m^2.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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