Comprehensive assessment and analysis of frequency fluctuation and voltage total harmonics distortion in Malaysia's grid-connected solar PV systems: an empirical study

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ABSTRACT

Grid-connected solar photovoltaic (GCPV) systems have become an essential part of modern electricity generation due to their ability to harness clean, renewable energy, reduce greenhouse gas emissions, and lower dependence on fossil fuels. In Malaysia, initiatives promoting small-scale GCPV adoption among residential, commercial, and industrial users have been notably successful. However, concerns regarding power quality (PQ) within GCPV-integrated environments remain insufficiently explored. This study presents a comprehensive evaluation of the impact of GCPV generation on frequency fluctuations and voltage total harmonic distortion (THD_V) within the Malaysian grid. The methodology involves empirical measurements of PQ at a selected GCPV installation, focusing on frequency fluctuation and THD_V, and compares the results against Malaysian and international standards. These measurements form the basis for further statistical analysis, which includes descriptive analysis, process capability analysis, and Pearson correlation analysis. The study aims to provide insights into grid stability, the influence of GCPV output on PQ, and the relationship between environmental factors and PQ deviations. Findings reveal that GCPV generation has minimal impact on grid PQ, which remains within acceptable limits set by relevant standards. Furthermore, no significant correlation was observed between GCPV output and PQ deterioration. The results contribute to a deeper understanding of PQ challenges in GCPV systems and offer valuable guidance for regulators and utility providers to support the development of effective mitigation strategies to ensure the continued stability and efficiency of Malaysia's evolving power grid.

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1. INTRODUCTION

Solar photovoltaic (PV) generation has become a crucial component of power generation due to its ability to harness renewable and clean energy, reduce greenhouse gas emissions, and decrease reliance on fossil fuels [1]–[3]. As the global transition toward sustainable energy accelerates, solar PV systems are increasingly integrated into power grids worldwide. However, the widespread adoption of grid-connected solar photovoltaic (GCPV) presents challenges, particularly regarding maintaining frequency stability and voltage total harmonic distortion (THD_V), which arises due to the volatility of PV generation that leads to imbalances between power supply and demand [4]–[6]. In recent years, driven by National Energy Policy

(NEP) 2022-2040 [7], Net Energy Metering 3.0 (NEM 3.0) [8], and SEDA Act (2011) [9], the increased adoption of GCPV has significantly boosted solar PV share in Malaysia's energy mix, as shown in Figures 1 and 2 [1], [10]. Figure 1 illustrates Malaysia's steady increase in solar PV generation growth from 2010 to 2023. Complemented by Figure 2, which shows the changing trend of energy mix in Malaysia over the same period, reflecting Malaysia's transition toward cleaner energy sources [10], [11].

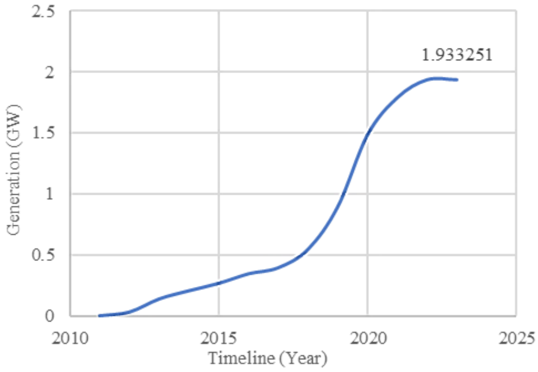

Figure 1. Solar PV growth trend in Malaysia

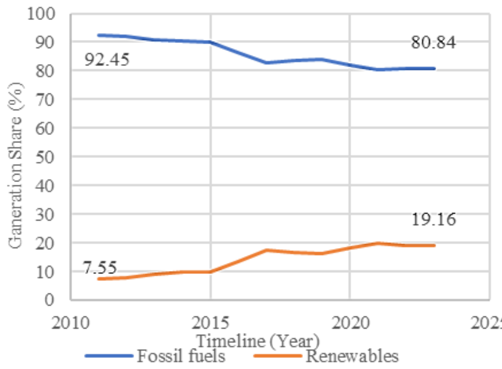

Figure 2. Power generation share trend in Malaysia

Frequency fluctuation refers to variations in a power grid's operating frequency of 50 Hz or 60 Hz caused by imbalances between electricity generation and consumption [12]. In GCPV systems, these fluctuations occur due to the volatility of solar PV generation, which changes throughout the day and with weather conditions [6]. Unlike traditional power generation, solar PV lacks the inherent inertia that helps stabilize grid frequency, making rapid changes in solar output more difficult to manage [4]. In extreme cases, solar PV generation can shift from 0% to 100% of its capacity within minutes, leading to sudden frequency deviations causing grid instability, increasing the risk of cascading failures or blackouts. Additionally, frequency variations may damage sensitive equipment, lower the efficiency of electrical devices, and degrade overall PQ [13], [14].

THD_V quantifies the deviation of a voltage waveform from its ideal sinusoidal shape by measuring the contribution of harmonic voltage to the fundamental voltage. THD_V in GCPV primarily originates from the switching operations of inverters during power conversion, particularly when operating under partial loads or suboptimal conditions. The power electronic components in the inverters, including switches and rectifiers, inherently generate harmonic distortion during operation. Excessive THD_V poses significant risks to the electrical system, causing voltage fluctuations, decreased system efficiency, and interfering with communication networks [15]. Additionally, it leads to overheating in transformers and motors through induced eddy currents, reducing the lifespan of capacitor banks, and potentially damaging sensitive equipment. For grid operators, elevated THD_V complicates system management, often necessitating additional mitigation measures such as active filtering or specialized transformer designs to maintain grid stability and PQ [5], [15]. Standards and guidelines enforce strict THD_V limits of less than 5%, implemented through advanced switching techniques and monitoring systems to minimize the adverse effects of THD_V due to high GCPV penetration [13], [16]–[18].

The (1)–(4) present fundamental formulas for evaluating THD_V within electrical systems. The (1) defines the voltage root mean square (V_{RMS}), which computes the effective voltage value in a circuit. The (2) calculates current harmonic distortion (THD_I), where the numerator aggregates harmonic current components and the denominator sums all current components. The (3) measures THD_V in a voltage scale with higher values indicating greater waveform distortion. The (4) expresses THD_V as a percentage of fundamental voltage, providing a standardized metric for assessing THD_V and PQ, which is a more common expression for reporting THD_V. These equations enable quantification and evaluation of THD_V for the development of mitigation strategies, especially in systems with non-linear loads or renewable energy sources, where harmonic distortion can cause equipment malfunction, overheating, and energy losses [5], [13], [19].

$$V_{rms} = \sqrt{\frac{1}{t}\int_0^t V^2\, dt} \tag{1}$$

$$THD_I = \sqrt{\frac{\sum_{n=2}^{\infty} I_n^2}{\sum_{n=1}^{\infty} I_n^2}} \tag{2}$$

$$THD_V(V) = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^2}{\sum_{n=1}^{\infty} V_n^2}} \quad (3)$$

$$THD_V(\%) = \frac{\sqrt{\sum_{n=2}^{\infty}(Vn.rms)^2}}{(V1.rms)} * 100 \quad (4)$$

Malaysia authorities had implemented several guidelines and regulations that outline technical specifications for GCPV installations to address frequency fluctuations and THD_V. These guidelines emphasize proper inverter design and grid compliance to minimize the adverse effects of harmonic distortion and frequency fluctuations [20], [21]. By enforcing these regulatory frameworks, Malaysian authorities aim to integrate GCPV into its power grid without compromising grid reliability, supporting the transition to a more sustainable energy generation [17].

Ensuring frequency stability in Malaysia's GCPV ecosystems presents a significant challenge. The intermittent nature of solar power, which fluctuates due to cloud movement, weather variations, and seasonal changes, can cause sudden surges or drops in power generation, making it difficult to maintain the national grid's 50 Hz frequency. Additionally, Malaysia's high humidity and frequent tropical storms further amplify these variations. An example of a typical climate in Malaysia is shown in Table 1 [22], [23]. The table shows that Malaysia experiences frequent rainfall, thunderstorms, and overcast conditions, which can reduce GCPV efficiency by limiting direct sunlight and increasing diffuse radiation. High temperatures further diminish panel performance due to heat-related losses. Despite these challenges, the country's strong equatorial solar irradiance, together with strong support from the government, is driving significant growth in solar generation in Malaysia [7], [11].

Another major challenge is integrating numerous distributed and small GCPV systems, as shown in Table 2, with Malaysia's grid infrastructure [11]. Many parts of the country still rely on conventional grid systems that were not designed to accommodate high GCPV penetration. The variance of infrastructure presents a technological challenge in maintaining frequency fluctuation, especially in areas with a high concentration of GCPV [3]. Although the improved policies and forecasting mechanisms assisted in managing frequency fluctuations, real-time response capabilities remain insufficient due to the slow pace of grid modernization and limited deployment of smart grid technologies [19], [24]. Additionally, gaps in regulations and policies hinder effective enforcement of grid compliance, particularly for distributed small-scale GCPV.

Maintaining THD_V within limits in Malaysia's GCPV generation also presents considerable challenges. Many lower-cost or older solar PV inverters lack advanced filtering and control mechanisms, leading to higher THD_V injections into the grid, potentially damaging sensitive equipment and reducing grid efficiency [24]. In regions with high GCPV penetration, poorly coordinated inverter control strategies can lead to harmonic resonance, exacerbating THD_V issues [25]. Higher cost for mitigation solutions, such as active power filters and inverters with harmonic compensation features, has hindered effective mitigation strategies. Furthermore, the lack of real-time monitoring and enforcement mechanisms for THD_V compliance makes it challenging to detect and mitigate excessive THD_V before they impact grid stability and consumer appliances [19].

Table 1. Malaysia climate information

Climate parameter	Maximum	Minimum
Ave. rainfall	365 mm/month	140 mm/month
Temperature	39.0 °C	19.6 °C
Wind speed	24.4 m/s	7.0 m/s
Precipitation	272 days	180 days/year
Thunderstorm	156 days/year	90 days/year

Table 2. Small-scale GCPV distribution in Malaysia

Location	Generation capacity (MW)	Location	Generation capacity (MW)
Johor	238.5	Perlis	45.3
Melaka	78.2	Kelantan	68.9
Negeri Sembilan	92.7	Terengganu	57.1
Selangor	312.4	Pahang	103.5
Perak	156.8	Sarawak	89.7
Kedah	124.6	Sabah	112

This study investigates frequency fluctuations and THD_V within an 11 kV/400 V distribution network connected to a 399 kWp GCPV system in Malaysia. The focus is limited to these two PQ parameters, excluding other aspects such as voltage fluctuations or power factor issues. The primary objective is to assess the impact of GCPV integration on frequency stability and THD_V levels using an empirical approach. Considering the intermittent nature of GCPV and the role of inverter-based power conversion, real-world grid data and detailed measurements were analyzed to evaluate system behavior. Statistical analysis, including descriptive analysis, process capability analysis, and Pearson correlation analysis, was applied to estimate the likelihood of frequency and THD_V exceeding standard limits. Findings offer valuable insights into PQ compliance in GCPV integrated networks and support the development of effective mitigation strategies and proactive grid management for maintaining grid stability [13], [26].

This study presents a unique contribution to PQ study by providing the combined empirical assessment of frequency fluctuation and THD_V in a 399 kWp GCPV installation within Malaysia's low-voltage network. Unlike previous works that typically analyze voltage variation or harmonic distortion in isolation, this paper integrates field PQ measurements with a comprehensive simulation–validation framework that includes real-time irradiance data from the Solcast API, PVSYST energy modelling, and PowerLog 5.9 data extraction. The incorporation of process capability indices and Pearson correlation analysis further distinguishes this study by offering a more rigorous statistical evaluation of PQ performance under actual GCPV operating conditions. Collectively, these contributions fill a significant gap in local PQ assessment literature and provide valuable insights for utilities, engineers, and policymakers in understanding grid stability as GCPV penetration increases.

2. METHODOLOGY

The research methodology employed in this study integrates empirical PQ measurements, statistical analysis, and standards-based evaluation to assess frequency fluctuation and THD_V in a GCPV system. The methodology consists of five main stages: site selection and system description, PQ measurement and data logging, GCPV simulation and validation, compliance evaluation against standards, and statistical analysis. Figure 3 illustrates the overall workflow.

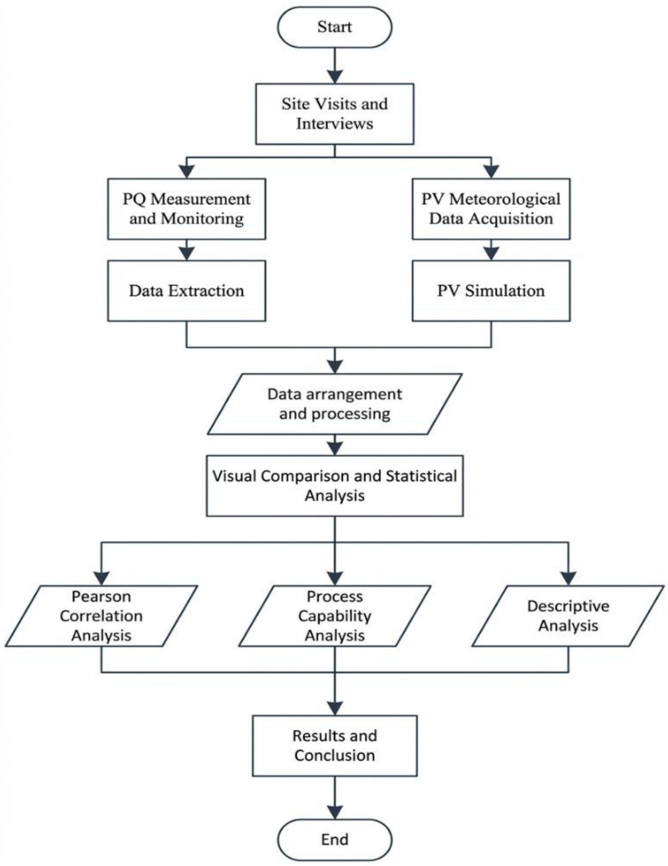

Figure 3. Research flowchart

2.1. Site selection and system description

A commercial rooftop GCPV installation rated at 399 kWp was selected as the case study. The system is connected to the 11 kV/400 V distribution network of the Malaysian utility grid. The installation consists of three 100 kW PV inverters operating in parallel, supplying power to the load and exporting surplus energy to the grid, as shown in Figures 4 and 5, which illustrate the general system configuration and the electrical connection diagram, respectively.

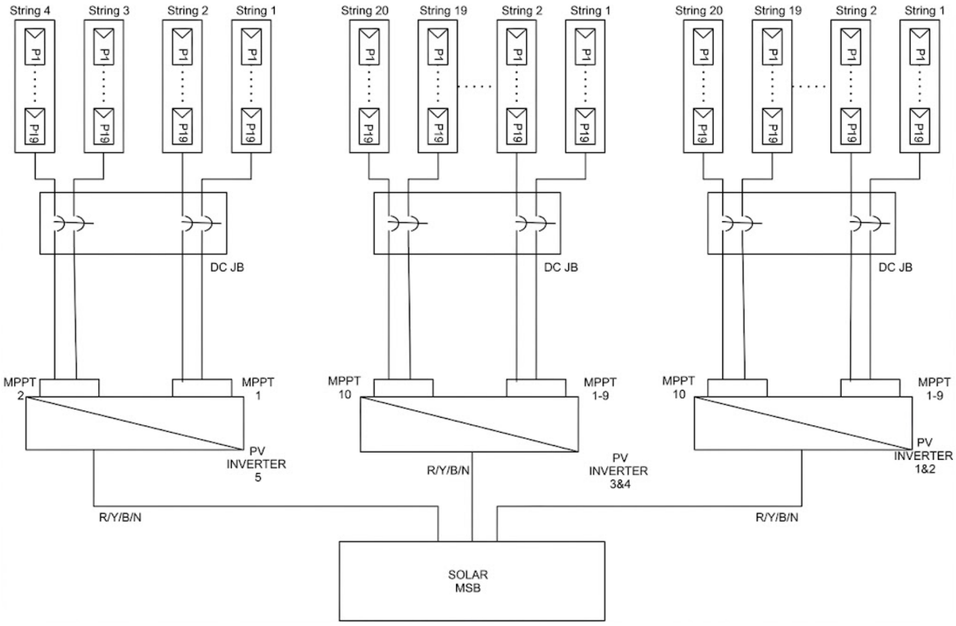

Figure 4. GCPV installation diagram

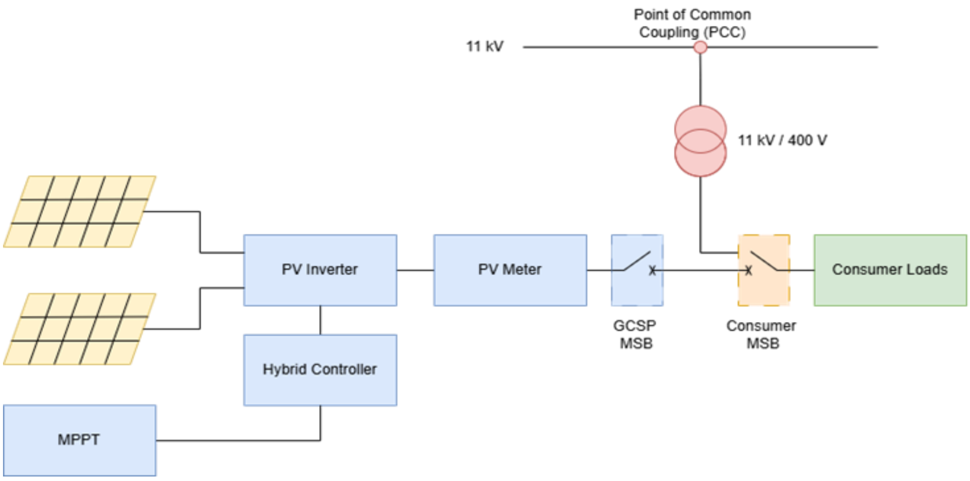

Figure 5. GCPV generic block diagram

2.2. PQ measurement and data logging

Power quality measurements were recorded at the main switchboard (MSB) using a Class A-compliant PQ analyzer, as shown in Figure 6. The instrument was configured to monitor frequency, voltage waveform distortion, and phase-by-phase THD_V. Measurements were logged in accordance with typical distribution network PQ observation practices to capture operational variations during daily GCPV generation cycles. In addition to physical logging, the recorded PQ data were extracted using PowerLog 5.9 software, which serves as the dedicated analytical interface for the PQ analyzer. PowerLog 5.9 was used to retrieve raw measurement files, visualize daily PQ trends, and export numerical values for frequency, RMS voltage, harmonic spectrum, and phase-specific THD_V for further statistical processing.

Figure 6. Installation of Fluke 435 PQA for PQ monitoring

2.3. GCPV simulation and validation

In addition to empirical PQ measurements, GCPV generation performance was simulated to validate the behavior of solar output during the monitoring period. Solar irradiance and weather parameters for the study site were retrieved using the SOLCAST API™, which provides time-series irradiance forecasts and historical weather datasets based on localized satellite estimation. The API data allowed the estimation of real-time irradiance trends corresponding to the PQ measurement window.

The exported irradiance profiles from SOLCAST API™ were subsequently used as inputs for PVsyst™ simulation, where the 399 kWp PV system parameters, including module specifications, inverter ratings, system losses, and orientation configurations, were modelled. PVsyst™ generated hourly solar energy output profiles that represent expected GCPV performance under the actual irradiance of the site.

To ensure accurate representation of GCPV generation, the simulated energy output from PVsyst™ was validated against the recorded daily energy production data obtained from the system operator. The comparison between simulated and recorded production served as a verification that the irradiance conditions, PV parameters, and system assumptions were well represented. This simulation validation step also ensured that any PQ variations observed during the study were correlated with realistic operating conditions of the GCPV system.

2.4. Standard-based compliance evaluation

The measured PQ parameters were evaluated against national and international standards, including frequency fluctuation and THD_V limits. Table 3 lists key standards for frequency fluctuation and THD_V, essential for power quality, reliability, and safety. Maintaining compliance ensures grid stability, prevents equipment failure, and enhances GCPV system efficiency, supporting long-term operational reliability and safety [19], [27].

Table 3. Specifications according to standards and guidelines

Standards and regulations	Frequency	THD_V
Electricity Supply Act 1990 (Akta 447) [28]	50 Hz ± 1%	N/A
Malaysia Distribution Code Amendment (2017) (MDC 2017) [29]	50 Hz ± 1%	≤5% for LV systems
Sustainable Energy Development Act 2011 (SEDA 2011) [11]	50 Hz ± 1%	N/A
TNB Electricity Supply Application Handbook 3.1 (ESAH 3.1) [21]	50 Hz ± 1%	≤5% for LV systems
IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (IEEE 519) [13]	N/A	≤5% for LV systems
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (IEEE 1547) [14]	50 Hz ± 1%	≤5% for distributed systems
Compatibility Levels for Low-Frequency Conducted Disturbances and Signalling in Public Low-Voltage Power Supply Systems (IEC 61000-2) [16]	50 Hz ± 1%	≤8%
Photovoltaic (PV) System Performance Monitoring – Guidelines for Measurement, Data Exchange and Analysis (IEC 61724) [30]	50 Hz ± 2%	N/A

2.5. Statistical analysis

To understand the influence of GCPV generation on PQ characteristics, descriptive statistics, process capability analysis, and Pearson correlation analysis were applied. These techniques evaluate numerical stability, identifying trends, probability of exceeding limits, and the relationship between PQ parameters and GCPV generation. Further enabling targeted mitigation and evidence-based decisions for a more resilient grid and optimized performance amid increasing GCPV integration [31].

Process capability indices, Cp, Cpk, Pp, and Ppk defined in (5)–(8) evaluate system performance against specified limits [26], [32], [33]. While Cp assesses potential capability under ideal centering, Cpk considers potential capability under actual centering. Pp and Ppk incorporate long-term potential capability variation, reflecting real-world performance [33]. These indices enable the assessment of PQ against standards, determine compliance, and reveal the PQ performance of a GCPV system. Ultimately, preventing equipment malfunctions, reducing downtime, and boosting efficiency. Tables 4 and 5 define these indices and their interpretation guidelines [12], [34].

$$Cp = \frac{(USL-LSL)}{6\sigma} \tag{5}$$

$$Cpk = \min\left(\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right) \tag{6}$$

$$Pp = \frac{(USL-LSL)}{6\sigma_{(overall)}} \tag{7}$$

$$Ppk = \min\left(\frac{USL-\mu}{3\sigma_{(overall)}}, \frac{\mu-LSL}{3\sigma_{(overall)}}\right) \tag{8}$$

The Pearson correlation coefficient (r), as shown in (9), is a statistical measure that quantifies the linear relationship between two variables. Enabling relationships evaluation between critical parameters and both internal and external influencing factors [35]. This analytical approach enables the identification of significant interdependence and supporting data-driven optimization of system performance, which are crucial for maintaining regulatory compliance while enhancing overall grid reliability through evidence-based decision-making [35], [36]. The definition and interpretation of (9) are explained in Tables 6 and 7 [31].

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2(y_i-\bar{y})^2}} \tag{9}$$

Table 4. Process capability indices formula variable definition

Symbol	Definition	Symbol	Definition
Cp	Process capability index	USL	Upper specification limit
Cpk	Process capability index (adjusted for centering)	LSL	Lower specification limit
Pp	Process performance index	μ	Process mean
Ppk	Process performance index (adjusted for centering)	Σ	Short-term standard deviation
		$\sigma_{(overall)}$	Long-term standard deviation

Table 5. Process capability indices values interpretation

Value	Interpretation
> 1.33	Excellent capability, capable of meeting specifications.
1.00 to 1.33	Marginal capability, meets specifications with some room for improvement.
< 1.00	Poor capability, not capable of meeting specifications and requires improvement.

Table 6. Pearson correlation coefficient variable definition

Symbol	Definition	Symbol	Definition
$\bar{y}$	Mean of variable y	x_i	Individual data point from variable x
y_i	Individual data point from variable y	$\bar{x}$	Mean value of variable x
r	Pearson correlation coefficient		

Table 7. Pearson correlation coefficient value interpretation

Coefficient	Interpretation	Coefficient	Interpretation
1	Perfect positive correlation	-0.01 to -0.29	Very weak negative correlation
+0.90 to 0.99	Very strong positive correlation	-0.30 to -0.49	Weak negative correlation
+0.70 to 0.89	Strong positive correlation	-0.50 to -0.69	Moderate negative correlation
+0.50 to 0.69	Moderate positive correlation	-0.70 to -0.89	Strong negative correlation
+0.30 to+0.49	Weak positive correlation	-0.90 to -0.99	Very strong negative correlation
+0.01 to 0.29	Very weak positive correlation	-1	Perfect negative correlation
0	No correlation		

3. RESULTS AND DISCUSSION

Figure 7 presents measured frequency and THD_V data alongside global horizontal irradiance (GHI) from SOLCAST API™ and simulated GCPV power output of PVsyst™ over 72 hours. The frequency remains stable within the utility grid specification of 50 Hz ±1%, indicating robust grid synchronization. THD_V across all phases ranged from 1.0% to 1.75%, significantly less than the 5% limit, confirming compliance with standards. The GHI and GCPV outputs exhibit expected daily cycles, with power generation closely tracking solar availability. Notably, frequency stability persists despite GHI and GCPV output variations, suggesting a limited impact on the grid. In contrast, THD_V shows a slight elevation during peak solar hours (08:00 hours –12:00 hours), likely due to inverter operation or GCPV to grid interactions during high generation. While these results demonstrate effective GCPV integration with no critical PQ degradation, visual analysis alone proves insufficient to establish precise correlations among parameters. Advanced statistics are recommended to quantify underlying relationships, particularly for THD_V's mild dependence on solar activity as seen in Figure 7. Such analysis would further validate system resilience and guide mitigation strategies for long-term grid stability.

To address the limitations of visual inspection, this study implements a comprehensive statistical framework for PQ assessment in GCPV systems. The methodology incorporates descriptive statistical analysis to characterize key parameters' stability, process capability analysis to quantify compliance with established regulatory thresholds, and Pearson correlation analysis to systematically evaluate potential relationships between solar generation variability and PQ indicators.

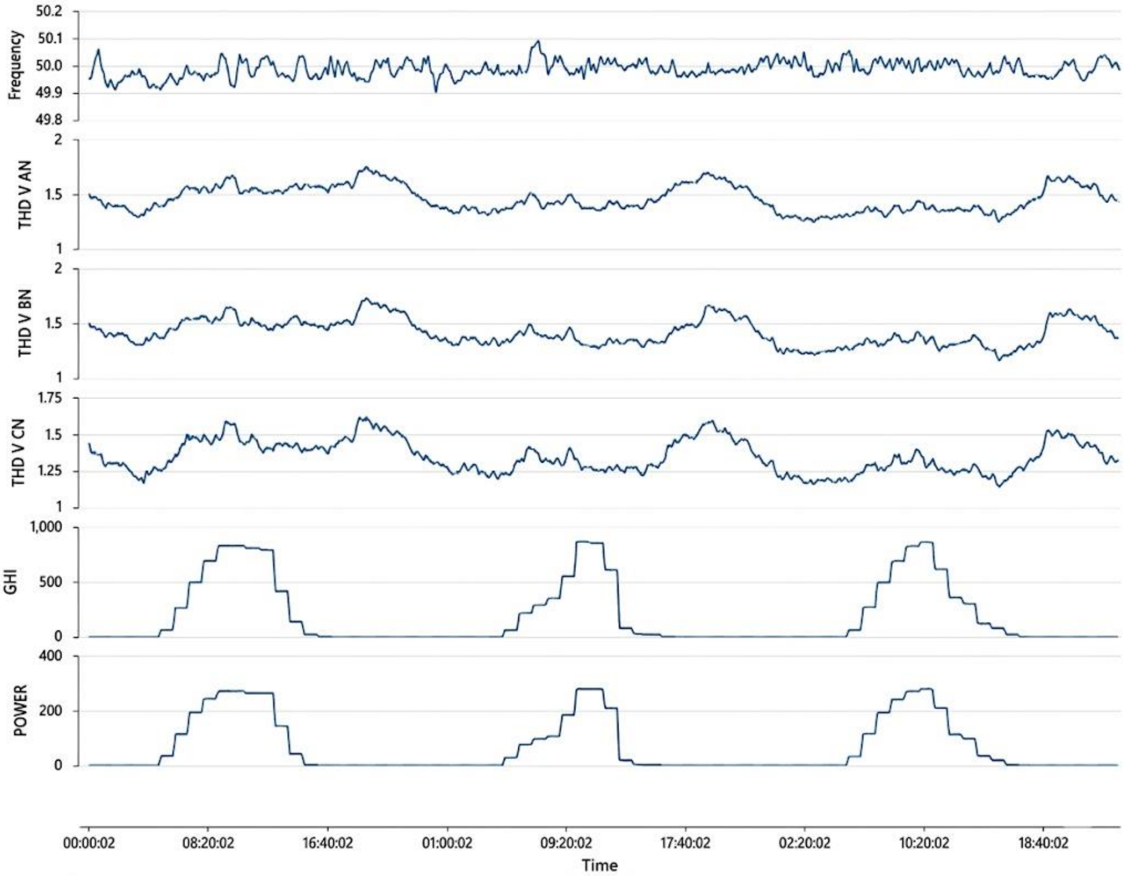

Figure 7. Combined time series data for the understudy GCPV

3.1. Descriptive analysis

Table 8 shows that the maximum, minimum, median, mean, and standard deviation of the system frequency are very close to the nominal specification value of 50.00 Hz ±1%, indicating tight frequency control. The maximum, minimum, median, mean, and standard deviation values of THD_V across the three phases are very close to each other and well below the maximum 5% limit set by standards and guidelines. However, the spread is slightly larger in THD_{VBN}, with a standard deviation of 0.122, compared to THD_{VAN}

and THD_{VCN}. This implies that THD_{VBN} experiences more variable distortion, which could suggest phase imbalance, varying load conditions, or inverter effects unique to that phase.

Table 9 shows how the skewness value in the descriptive analysis translated [32], [37]. The near-zero skewness values indicate normal distributions of frequency and THD_V data. However, THD_{VBN} exhibits slightly higher variability, as evidenced by its larger standard deviation, suggesting occasional elevated distortion events. The consistent elevation in THD_{VBN} relative to other phases may indicate phase-specific operational influences. Recommended mitigation strategies, including phase load balancing and inverter performance analysis, might be implemented to improve THD_{VBN}.

While descriptive statistics offer an overview of parameter behavior, it lacks the discriminative ability to assess dynamic system interactions. These metrics cannot capture time-dependent variations caused by external factors, nor can they detect transient events or underlying patterns critical for PQ diagnosis in GCPV systems. Furthermore, descriptive analysis provides no temporal compliance trends or violation probabilities insights, which are better derived from process capability and correlation analyses.

Table 8. Descriptive analysis result table

Parameter	Mean value	Standard deviation	Minimum value	Median value	Maximum value	Skewness (γ)
Frequency (Hz)	49.988	0.0303	49.901	49.983	50.0932	0.20
THD_{VAN} (%)	1.459	0.119	1.245	1.431	1.754	0.36
THD_{VBN} (%)	1.413	0.122	1.159	1.387	1.733	0.41
THD_{VCN} (%)	1.350	0.113	1.142	1.321	1.622	0.39

Table 9. Skewness value interpretation table

Skewness value (γ)	Interpretation	Relevance to power quality data
$\gamma \approx 0$	Symmetrical distribution	Ideal grid condition for frequency and THD_V
$\gamma > 0$	Positive skew (right tail)	May indicate occasional spikes of frequency or THD_V
$\gamma < 0$	Negative skew (left tail)	Rare in power systems; could suggest measurement bias
$\|\gamma\| < 0.5$	Near normal	Acceptable for steady-state power system
$\|\gamma\| \geq 1$	Severe skew	Suggests frequency or THD_V instability or disturbance in the system

3.2. Process capability analysis

The process capability analysis for the GCPV system frequency, as in Figure 8, assesses how well the frequency fluctuates around 50 Hz ±1%. Both the overall and within standard deviations are very low, indicating a stable and consistent frequency during the measurement period. The process performance metrics (PPM) values are all equal to 0.00, showing that every measured frequency meets the specification. All key capability metrics are significantly higher than the benchmark value of 1.33, indicating excellent capability to maintain the frequency within specification. Specifically, Pp values of 5.49 and Ppk values of 5.36 show that the frequency is not only capable of maintaining the specification but also centered well within the limits, implying that the system's frequency exhibits exceptional stability and compliance with regulatory standards.

The analysis predicts virtually zero probability of future non-compliance, as evidenced by the 0.00 PPM values for both LSL and USL at 95% confidence. These results assure continued compliance under current operating conditions. However, it remains prudent to implement periodic monitoring to detect any potential variation due to changes in system loading or generation patterns. The absence of observed violations and the minimal risk of future non-conformance suggest that the current control mechanisms for frequency regulation are highly effective and provide valuable information for system operators in maintaining grid stability and planning for increased renewable energy integration.

The process capability analysis of THD_V demonstrates exemplary compliance with the established 5% limit across all three phases, as evidenced in Figures 9-11. The analysis reveals exceptionally stable performance, characterized by minimal process variation of less than 0.5% and zero non-conforming, with PPM equal to 0.00. Capability indices substantially exceed the benchmarks, with Pp values ranging from 6.85-7.36, and Ppk values ranging from 3.87-4.09, indicating not only robust process capability but also optimal centring within specification limits. These findings statistically validate the system's ability to maintain THD_V compliance, with a near-certain probability of continued adherence under current operating parameters. However, given the dynamic nature of GCPV systems, it is recommended to implement continuous monitoring to detect emerging harmonic distortion trends and mitigate emerging PQ issues proactively in evolving power networks.

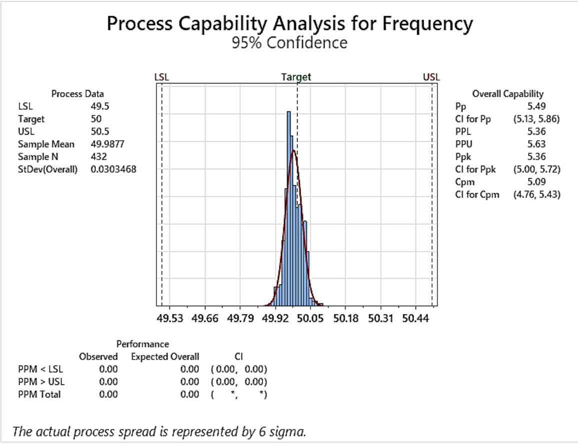

Figure 8. Process capability analysis of frequency fluctuation

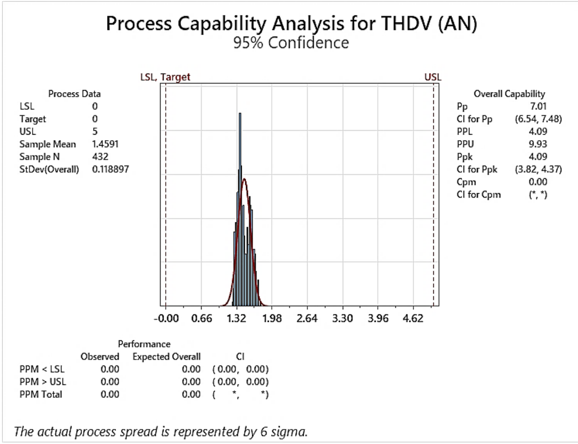

Figure 9. Process capability analysis of THD_{VAN}

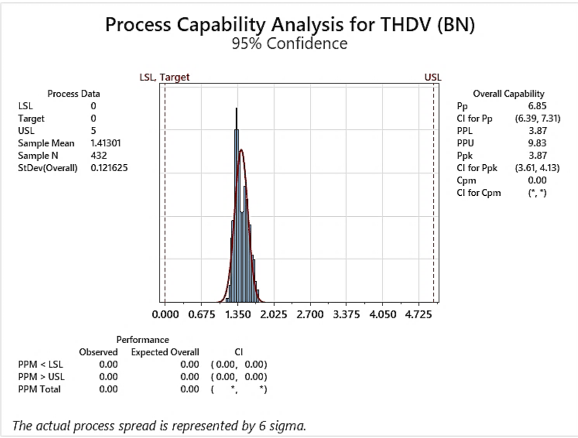

Figure 10. Process capability analysis of THD_{VBN}

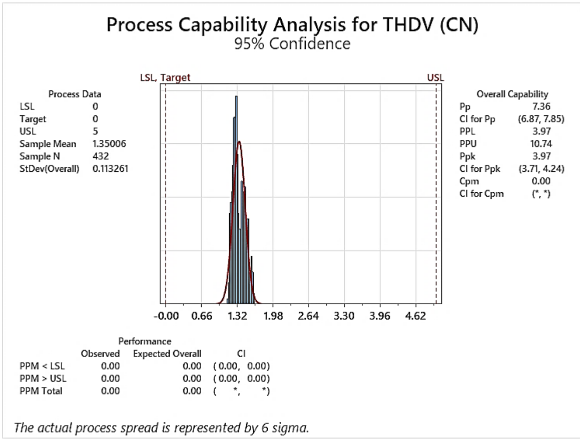

Figure 11. Process capability analysis of THD_{VCN}

3.3. Pearson correlation analysis

The matrix plot in Figure 12 examines interactions between frequency fluctuations, GHI, and Injected Power. Scatter plots reveal no discernible linear trends between frequency and either GHI or injected power, with data points randomly distributed across the 49.9–50.1 Hz range. This visual pattern suggests negligible correlation between frequency stability and solar generation parameters. Weak positive correlations (r = 0.166 for frequency-GHI, r = 0.159 for frequency-injected power) confirm the negligible influence of solar variability on grid frequency. In contrast, GHI and injected power exhibit near-perfect linear correlation, reflecting expected proportional relationships in PV systems. These findings indicate that while GHI directly determines power injection, its effect on frequency remains insignificant, likely attributable to robust grid regulation and the limited GCPV penetration level in this study. The results underscore the effectiveness of existing frequency control mechanisms in mitigating solar generation variability.

Figures 13–16 present scatter plots demonstrating distinct patterns in THD_V relationships. The random dispersion of THD_V data points against both GHI and injected power reveals no discernible correlation, suggesting that THD_V levels are mainly driven by inverter switching behavior, network impedance distribution, and prevailing load conditions. In contrast, inter-phase THD_V comparisons exhibit tightly clustered linear distributions, forming well-defined diagonal bands that visually confirm strong harmonic coupling between phases. Quantitative analysis reinforces these observations through Pearson correlation coefficients. The exceptionally high r-values between phases demonstrate near-perfect harmonic synchronization across the three-phase system. This phase-to-phase consistency likely results from identical inverter control and balanced system loading. Conversely, the negligible correlation indices between THD_V and solar generation parameters statistically confirm that GHI and injected power variations exert minimal influence on THD_V levels. These findings yield critical insights for GCPV system operation. THD_V stability remains largely unaffected by GHI variability, indicating that harmonic mitigation strategies should focus on power electronic controls and grid interface characteristics rather than generation levels. The strong inter-phase THD_V correlation suggests that mitigation measures applied to one phase may prove equally effective across all phases, simplifying THD_V control implementation. The results underscore the importance of maintaining inverter performance and robust grid integration practices to ensure consistent THD_V management.

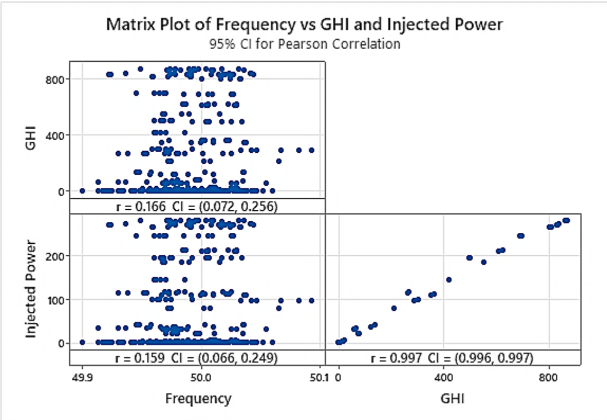

Figure 12. Frequency vs GHI vs injected power scatterplot

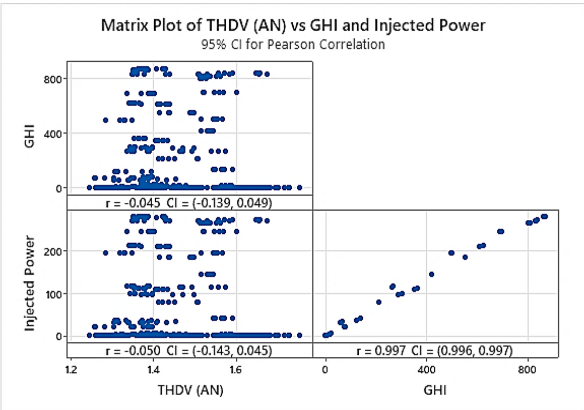

Figure 13. THD_{VAN} vs GHI vs injected power scatterplot

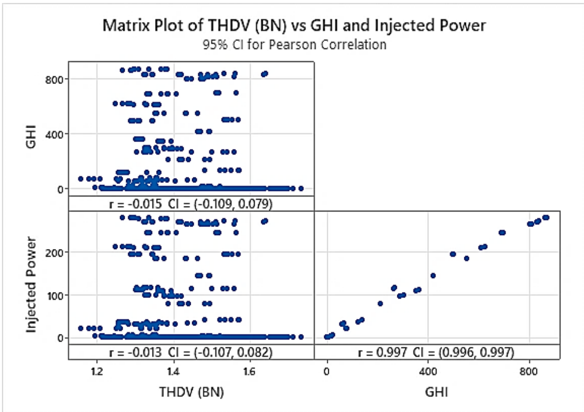

Figure 14. THD_{VBN} vs GHI vs injected power scatterplot

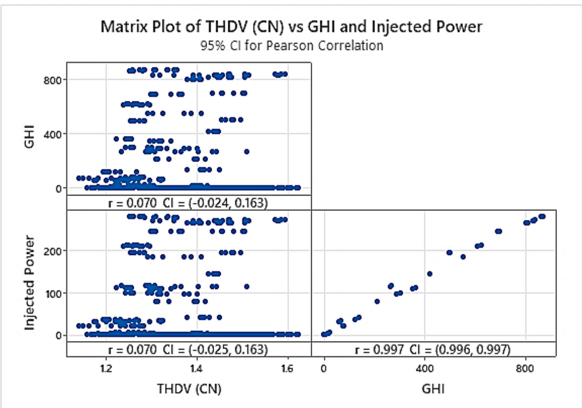

Figure 15. THD_{VCN} vs GHI vs injected power scatterplot

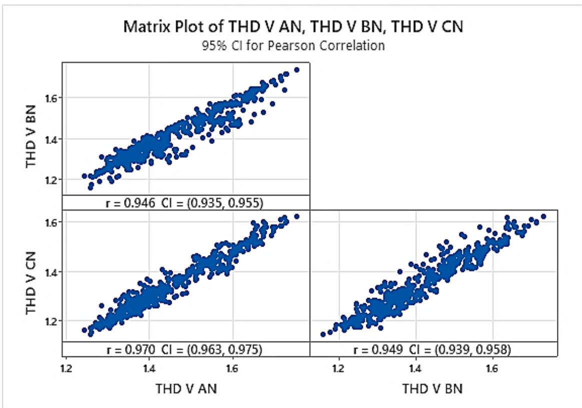

Figure 16. THD_{VAN} vs THD_{VBN} vs THD_{VCN} scatterplot

4. CONCLUSION

This study demonstrates that the evaluated GCPV system maintains excellent PQ, with stable frequency and THD_V regulation. The negligible correlation ($r \approx 0$) between PQ parameters and GHI confirms effective mitigation of renewable intermittency impacts. Strong inter-phase THD_V correlations reveal system-wide THD_V consistency, attributable to balanced operation and uniform grid interface characteristics. The integrated analytical approach provides a comprehensive PQ evaluation framework. While results indicate robust performance, the single-site study limits broader applicability. Future research should examine multiple co-located installations to better understand aggregated PV impacts on grid stability, particularly in regions with high renewable penetration. These findings offer valuable insights for utilities and system operators, highlighting both the PQ reliability of modern GCPV systems and the need for continued monitoring as deployment scales. The methodology presented serves as a practical foundation for ongoing power quality assessment in evolving power networks. In addition, the use of process capability indices and correlation analysis offers a more quantitative basis for evaluating inverter-grid interaction, which may help refine monitoring or commissioning requirements. These contributions can help guide regulators and utilities in strengthening upcoming revisions of MDC 2017 and ESAH 3.1 to better support Malaysia's growing GCPV deployment.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hasif Mohamad	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available on request from the corresponding author, [HM]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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