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# Investigating The Impact Of Varying Pv Operating Power On Power Quality (Voltage And Current Harmonics)

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***Abstract**- The increasing integration of photovoltaic (PV) systems into low-voltage distribution networks introduces harmonic distortions that affect overall power quality. This study investigates the impact of varying PV operating power on voltage and current harmonic distortions in a grid-connected PV system. The main objective is to analyze how changes in inverter loading influence total harmonic distortion (THD) levels under different operating conditions. A 3-kW grid-connected PV array was modeled and simulated using MATLAB/Simulink to evaluate system performance at half-rated (0.5P), rated (1P), and double-rated (2P) operating powers. The system includes a voltage-source inverter equipped with an LCL filter to ensure harmonic attenuation and smooth grid interfacing. Simulation results reveal that operating at reduced power (0.5P) increases current THD, while higher loading conditions (2P) significantly lower THD values. Specifically, increasing the inverter power from 0.5P to 2P resulted in approximately a 24% reduction in current THD, with voltage THD remaining within IEEE Std 519 permissible limits. The findings indicate that inverter loading and DC-link behavior substantially influence harmonic emissions. It is concluded that maintaining PV inverters near their optimal operating points and incorporating appropriate filtering or advanced control techniques can effectively enhance power quality and ensure compliance with grid standards.*

***Index Terms- Photovoltaic (PV) Systems, Power Quality (PQ), Total Harmonic Distortion (THD), Grid-Connected Inverters, Distributed Generation (DG)***

## 1. INTRODUCTION

The rapid expansion of photovoltaic (PV) generation in current power systems is a key step toward a more sustainable and renewable electricity supply. As nations endeavour to diminish reliance on fossil fuels, PV systems have emerged as one of the most extensively embraced renewable energy technologies, owing to their scalability, environmental sustainability, and economic efficiency [1]. Furthermore, the increasing deployment of inverter-based distributed generation has changed the architecture of power systems [2]. However, integrating PV systems into existing distribution networks has created new technical problems, especially those relating to power quality [3]. Electricity-electronic inverters connect PV systems to the grid, which is different from traditional synchronous generators. The way these inverters work can have a big impact on the reliability and quality of the electricity that is sent to customers.

Power quality (PQ) in electrical systems is how well the voltage, current, and frequency stay within acceptable ranges. In dispersed networks that use PV, it is getting harder to keep the power quality high because of changes in solar irradiation, inverter switching characteristics, and load demand [4]. Harmonic distortion is one of the most important problems among these concerns. The non-linear operation of inverter switches is what causes harmonics [5]. Such distortion can change the shape of current and voltage waveforms, increase system losses, and cause sensitive equipment to wear out or break down too soon [6]. These distortions spread across the distribution network, affecting not just the PV system's immediate connection point but also nearby consumers and equipment.

When the power levels change, like in the early morning, when it's cloudy, or when it's only partially shaded, the inverter may not switch as efficiently as it could. When the inverter is running at a lower power level, its pulse-width modulation (PWM) regulation doesn't work as well, which causes higher-order harmonics to be injected into the grid [7]. These harmonics raise the total harmonic distortion (THD) of both voltage and current. On the other hand, when inverters work close to or beyond their rated power, the switching behavior tends to settle [8]. This improves harmonic performance and lowers THD. Therefore, the operating power level of PV systems is very important for how electricity quality functions in distribution networks.

The issue is especially noticeable in low-voltage (LV) distribution systems with more than one PV installation. When numerous inverters work together under partial load situations, they can cause a lot of harmonic amplification, voltage distortion, and resonance phenomena [9]. Furthermore, the fact that solar energy is only available at certain times makes voltage fluctuations, flicker, and frequency deviations worse [10], making it even harder to control power quality. If these problems aren't handled effectively, they can make the grid less reliable, hurt customer happiness, and make distributed generation systems less efficient [11].

Even though PV systems are becoming more common in modern grids, most of the research that has been done so far has been on inverter topology, maximum power point tracking (MPPT), and energy conversion efficiency. Very little research has been done on how inverter loads affect harmonic distortion. Because of this, we don't know enough about how different PV operating power conditions affect voltage and current harmonics in real-world grid-connected situations. Understanding this relationship is essential for developing the best inverter management techniques, improving power quality compliance, and ensuring that renewable-based distribution systems remain stable over time.

This study aims to investigate the impact of varying PV operating power on power quality, particularly with respect to voltage and current harmonic distortion in grid-connected systems. By analyzing the harmonic behavior of PV inverters under different load conditions, the study seeks to establish a correlation between operating power levels and THD performance. The findings are expected to guide system designers and utility operators in developing effective operational strategies to minimize harmonic distortions and enhance inverter-based grid integration.

The significance of this study lies in its potential to provide practical insights for enhancing power quality in PV-integrated distribution networks. Understanding how inverter loading influences harmonic generation will enable the formulation of design standards and operational guidelines that optimize inverter utilization and mitigate power quality issues. Furthermore, the results of this study will be valuable to enforce PQ regulations such as IEEE Std 519-2014 and IEC 61000, ensuring the reliable and sustainable operation of distributed renewable energy systems.

## 2. LITERATURE REVIEW

### 2.1 Overview of Power Quality in PV-Integrated Systems

As photovoltaic (PV) generation becomes more common in modern power networks, new operational and technological problems relating to power quality (PQ) have been created. Power quality is the measure of how well the voltage, current, and frequency of a power system meet specified standards and stay within acceptable ranges [12]. Keeping PQ up to date is important for making sure that both the power supply and the end-user equipment work well and reliably. In conventional power systems characterized by synchronous generators, PQ is inherently facilitated by the system's intrinsic inertia and reactive power compensation, which assist in stabilizing voltage and frequency fluctuations [13]. But as increasingly distributed generation is done with inverters, the way PQ works has altered a lot, which is a problem for both network operators and end users.

Power electronic inverters connect PV systems to the grid. These nonlinear devices utilize high-frequency switching to transform DC energy from solar panels into AC energy suitable for grid use [4]. This conversion technique is efficient, but it causes problems with power quality, like voltage changes, current harmonics, and flicker. The quality of the power sent to the grid depends a lot on how well the inverter works and how it is controlled. The amount of harmonic distortion added to the network can be greatly affected by things like switching frequency, pulse-width modulation (PWM) method, and DC-link voltage stability [7]. Consequently, inverter design and operational circumstances are pivotal in ensuring PQ compliance in PV-integrated systems.

Also, the variability of solar energy, which depends on the weather, makes it harder to maintain high power quality. Changes in solar irradiance generate changes in power output, which produce voltage sags, swells, and flickers in the distribution network [4][14]. In weak networks or places with a lot of PVs, these changes can also cause reverse power flow and imbalanced voltage, especially when the load and generation don't match. Subsequently, while PV technology helps with energy diversification and protecting the environment, adding it to the grid makes the relationship between generation dynamics and network stability more complicated [15]. These problems show how important it is to look at how power quality changes when PV systems are used in different ways, especially when it comes to harmonic distortion and inverter performance.

### 2.2 Harmonic Distortion in Grid-Connected PV System

Harmonic distortion is one of the most common problems with power quality in grid-connected PV systems. This happens when nonlinear loads or switching devices cause the current or voltage waveforms to diverge from the ideal sinusoidal shape. Because PV inverters are nonlinear components, they create harmonics throughout the conversion process [5][7]. This is mostly because they switch at high frequencies. These harmonics alter the current waveform that enters the grid. Inappropriate handling can allow them to propagate throughout the distribution network, causing harm to both the utility and its customers. The Total Harmonic Distortion (THD) is a major metric used to measure this impact. It is the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency [16].

Excessive harmonic distortion can cause numerous problems in power systems. High current THD makes conductors and transformers lose more energy as heat, which shortens the life of the equipment [17]. Voltage harmonics, on the other hand, can cause sensitive electrical devices to malfunction, measuring tools to yield incorrect readings, and protective relays to operate incorrectly [11]. Furthermore, harmonic distortion can exacerbate resonance situations by interacting with the system's impedance at specific frequencies, thereby worsening voltage distortions [9]. These negative impacts highlight the importance of maintaining THD levels within the limitations defined by IEEE Std 519-2014, which stipulates that current harmonics should not exceed 5% and voltage harmonics should not exceed 3% in systems below 69 kV.

But it's challenging to keep harmonic levels under acceptable limits in PV systems because they work in a dynamic way. When there is partial shade or low irradiance, the inverter works at lower power levels [7]. The result makes the nonl inearity of switching more noticeable, which increases harmonic emissions. Furthermore, harmonic injection is worse when the grid voltage changes and the grid is weak, which makes it extremely difficult to meet PQ criteria [5]. Therefore, factors beyond the inverter's design influence the amount of harmonic distortion. The strength of the grid, changes in load, and the inverter's control mode also have an impact. This diversity underscores the necessity to examine harmonic behavior at various PV operating power levels to determine optimal inverter performance zones and effective mitigation measures.

### 2.3 Influence of Inverter Operating Power on Harmonic Generation

The inverter operating power is a fundamental determinant of harmonic behavior in PV-integrated systems. At reduced load or partial operating conditions, inverters exhibit inefficient switching and unstable modulation due to a lower DC-link voltage and poor utilization of semiconductor devices [4][18]. This inefficiency results in non-sinusoidal output currents with increased high-order harmonic content, which contributes to elevated THD levels at the grid connection point [19]. In contrast, when the inverter operates closer to its rated capacity, the switching devices function more linearly, modulation depth stabilizes, and the resultant current waveform becomes smoother and more sinusoidal, leading to reduced harmonic distortion [20].

Empirical and simulation-based studies have confirmed that harmonic distortion inversely correlates with the inverter’s operating power. [[19] observed that operating PV inverters at 50% of their rated power led to a 20–25% increase in current THD compared to full-load operation. [[20] also found that when PV inverters are pushed close to their maximum output, modulation control gets better, which improves harmonic performance and cuts down on the production of higher-order harmonics. The stable DC-link voltage and the efficient use of switching states in the PWM algorithm largely contribute to this improvement [18]. Therefore, maintaining the inverter at optimal operating conditions is crucial for minimizing harmonic emissions and ensuring compliance with PQ standards.

Practical PV systems rarely operate at constant power levels due to fluctuating solar irradiance. During periods of low sunlight, such as early morning or cloudy conditions, inverters often operate below their rated output, causing an increase in THD [7]. Moreover, the dynamic interaction between inverter loading, switching frequency, and grid impedance further influences harmonic propagation in the network. These findings emphasize that inverter loading conditions must be considered in PQ assessment frameworks and that designing inverters with adaptive control schemes capable of maintaining low THD across a wide power range is essential for improving the harmonic performance of PV-based distributed systems.

### 2.4 Cumulative Effects of Distributed PV Systems on Power Quality

In distribution networks with multiple grid-connected PV systems, harmonic interactions among inverters can create cumulative effects that significantly deteriorate overall power quality. Each inverter injects harmonics of specific orders depending on its control and switching pattern [21]. When multiple inverters operate simultaneously on the same feeder, the superposition of these harmonics may lead to constructive interference, thereby amplifying certain harmonic components [9]. This collective harmonic amplification is particularly pronounced in low-voltage (LV) distribution networks where line impedance is relatively low, allowing harmonic currents to propagate easily.

Several factors, such as the number of connected inverters, their synchronization, and operating power levels, influence the degree of cumulative distortion. During periods of low irradiance, when most PV units operate under partial load, harmonic emissions from individual inverters tend to increase, thereby magnifying the total harmonic distortion at the Point of Common Coupling (PCC) [22]. Systems lacking proper harmonic filtering or compensation mechanisms exacerbate this effect. The resulting voltage distortion can affect not only the PV installation itself but also neighboring non-linear loads and sensitive consumer equipment connected to the same distribution feeder.

Additionally, distributed PV systems can cause secondary PQ issues such as voltage flicker, unbalance, and reactive power instability. The random nature of solar generation, combined with the time-varying load profile of the network, can induce voltage fluctuations that degrade PQ performance over time. The cumulative nature of harmonic and voltage disturbances thus poses significant challenges for network operators, especially in areas with high PV penetration. Hence, a deeper understanding of how multiple inverters interact under varying power conditions is essential for designing grid codes, monitoring frameworks, and mitigation techniques to preserve PQ in distributed energy systems.

### 2.5 Role of Filtering and Control Techniques in Harmonic Mitigation

Harmonic filtering is one of the most widely applied techniques for reducing the adverse effects of inverter-generated harmonics in grid-connected PV systems. Among available options, the LCL filter is preferred due to its superior ability to attenuate high-frequency components compared to simpler LC filters [23]. The filter's inductance-capacitance configuration allows for effective isolation between the inverter and grid, significantly reducing current ripple and smoothing the output waveform. However, the design of LCL filters must be carefully optimized to avoid resonance issues and ensure compatibility with the inverter's switching frequency, grid impedance, and operating power range.

Beyond passive filtering, researchers have developed active and hybrid filtering strategies that combine conventional filter designs with control-based compensation mechanisms. Active filters utilize controlled current sources or voltage converters to inject compensating signals that cancel harmonic components in real-time. When integrated into the inverter's control architecture, these filters can dynamically adjust to varying load and generation conditions, maintaining THD levels within IEEE standards [24]. Hybrid filters, which combine passive and active components, offer an optimized balance between cost and performance, making them particularly suitable for PV-based distributed generation systems.

Advanced control techniques, such as proportional-resonant (PR) control, repetitive control, and adaptive PWM modulation, have also emerged as effective methods for harmonic suppression. These techniques improve inverter performance by adjusting switching frequency, phase angle, and modulation index to minimize harmonic content in the output current. Recent advancements in artificial intelligence (AI) and machine learning have improved these methods even more, allowing for predictive harmonic compensation and adaptive parameter tuning in changing operating conditions. By integrating these control mechanisms, PV systems can maintain high PQ even under fluctuating irradiance and load scenarios, ensuring reliable and harmonically stable grid operation.

## 3. MATERIALS AND METHODS

### 3.1 Materials

The MATLAB/Simulink environment is used in this research to create a thorough model of the PV system and all its constituent parts. The LCL filter, which is intended to reduce harmonic distortion and guarantee grid compliance, is integrated with the photovoltaic array and the inverter with sophisticated control techniques. To assess the effects of power quality and the efficacy of filtering strategies under various PV penetration scenarios, this model is additionally connected to a low-voltage (LV) distribution feeder.

#### 3.1.1 Description of LV Distribution System

The system used for the investigation consists of a 3kW photovoltaic array system, a voltage source inverter (VSI), line impedance and the grid. The VSI is rated at 3kW with an inductance capacitance and inductance filter configuration used for filtering harmonics from the VSI. The system is shown in Figure 1. Table 1 also depicts the parameters of the system.

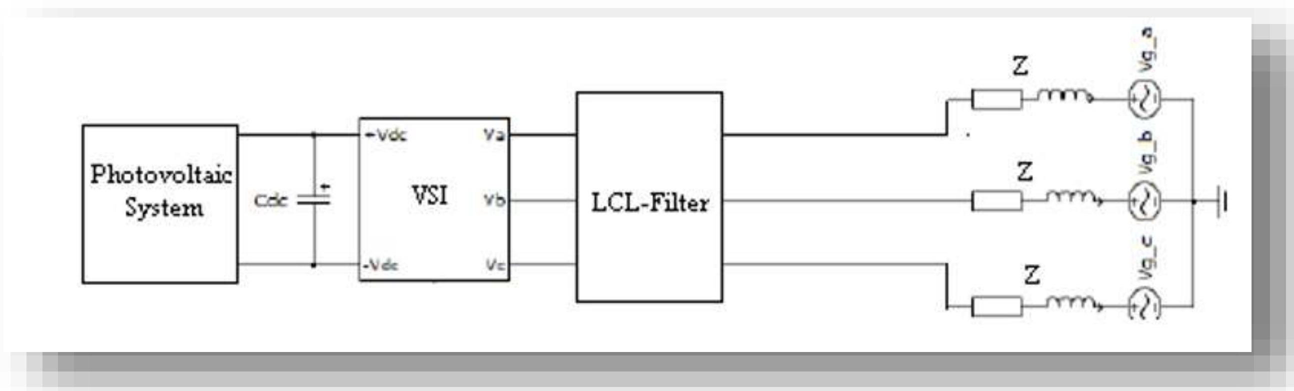

Figure 1: Schematics of the System

### 3.2 Method

#### 3.2.1 Effect of operating power of inverter on power quality

Input power $P_{IN}$ comes from the DC source (PV, battery, etc.):

$$P_{IN} = V_{DC} * I_{DC} \tag{1}$$

If $Pin$ drops but the inverter is commanded to keep the same AC output power, the DC-link voltage (Vdc) tends to fall (unless the current increases to compensate).

Suppose nominal inverter target $P_{SET}$ but actually it is;

$$P_{IN} = P_{SET} - \Delta P \tag{2}$$

In the steady-state approximate chain;

$$\Delta P \rightarrow \Delta V_{dc} \rightarrow \Delta V_{rms} \text{ nonlinear } \rightarrow \text{THD}\uparrow, \text{Pf}\downarrow, \text{unbalance}\uparrow \tag{3}$$

To quantify numerically by stepping $\Delta P$ in a time-domain model in MATLAB/Simulink, the equations applying the equations above, and extracting the power-quality metrics.

For a sinusoidal PWM inverter, the fundamental RMS output voltage is:

$$V_I \approx \frac{M * V_{DC}}{2 * \sqrt{2}} \tag{4}$$

where $M$ is the modulation index.

When Vdc falls, the controller tries to keep V1 constant by increasing M. If M tends to 1, it reaches the modulation limit (saturation), Beyond this limit, the waveform distorts (clipping, flat-topping), introducing harmonics**,** especially lower-order ones (3rd, 5th, 7th) plus switching harmonics.

If the inverter is supplying a constant output current, and $P_{IN}$ changes due to Vdc variations.

For near-linear PWM, switching harmonics scale with $M$ ;

$$V_h \alpha \; M^k$$

K is approximately 1 for low-order PWM harmonics.

$$THD \approx \frac{\alpha M}{\frac{M * V_{DC}}{2 * \sqrt{2}}} = \frac{\beta}{V_{DC}} = \frac{1}{P_{IN}} \tag{5}$$

This shows THD increases inversely with available input power when the output demand is fixed.

## 4. RESULTS AND DISCUSSION

### 4.1 The Impact of varying the PV operating power on the power quality (harmonic distortion of voltage and current)

Figures 1 and 2 illustrate the voltage and current Total Harmonic Distortion (THD) when the PV system is operating at half of the inverter's rated power (0.5P). The results indicate that the current THD increases under reduced operating power conditions, as shown in Figure 2. This observation suggests that a lower inverter output relative to its rated cap acity leads to higher harmonic injection into the grid, likely due to the less efficient switching operation of the inverter at partial load, which amplifies higher-order harmonics. Consequently, operating the inverter at low power can negatively impact the power quality at the point of common coupling (PCC).

Figures 3 and 4 present the voltage and current THD when the inverter operates at twice its rated power (2P). In this scenario, the results demonstrate that current THD at the PCC decreases, remaining well below the IEEE Std 519-2014 limits, indicating improved harmonic performance at higher operating levels. This trend confirms that inverter operation closer to or above rated power enhances the quality of current injections by reducing harmonic distortion, likely due to the more stable switching behavior and improved modulation efficiency at higher load.

Figure 5 quantifies the percentage difference in current THD between the 0.5P and 2P operating points. The analysis shows a reduction in THD of approximately 24% when increasing the operating power from half to twice the rated capacity, highlighting the significant effect of operating conditions on the harmonic performance of grid-connected PV inverters. These results emphasize the importance of considering inverter loading conditions in power quality assessment and suggest that optimal inverter sizing and operating strategies are critical for minimizing harmonic distortion in LV distribution networks.

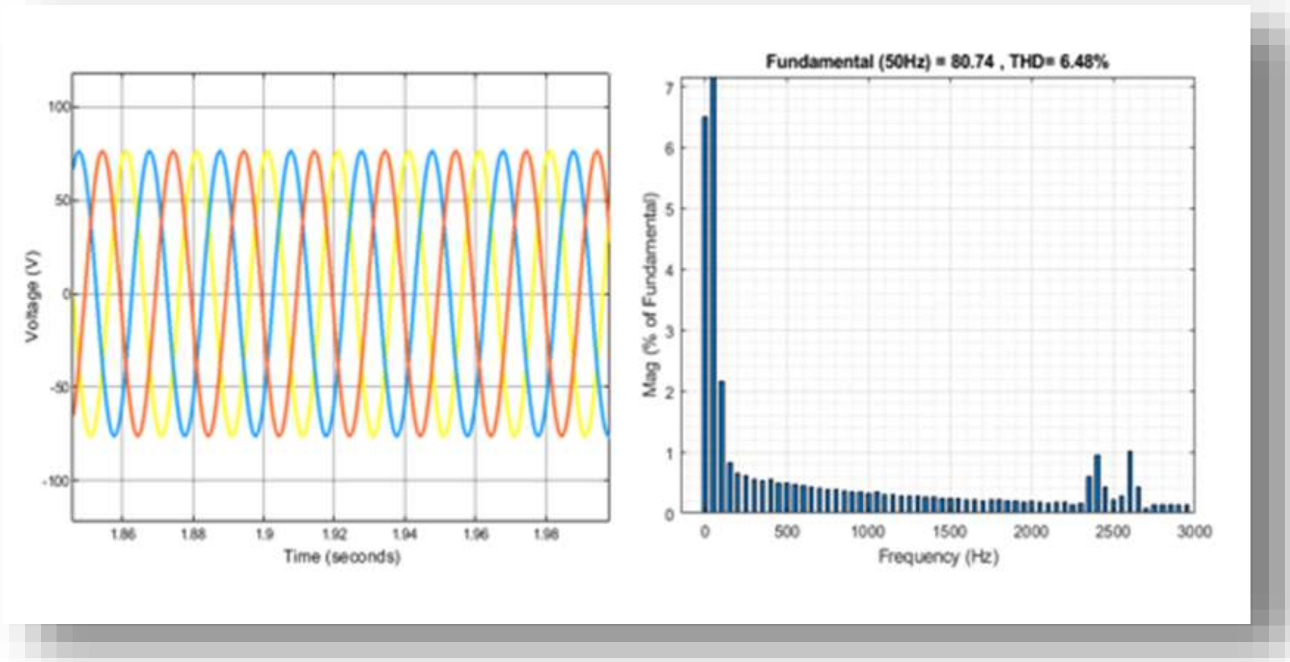


Figure 1: Voltage, and VTHD at 0.5P with LCL Filter

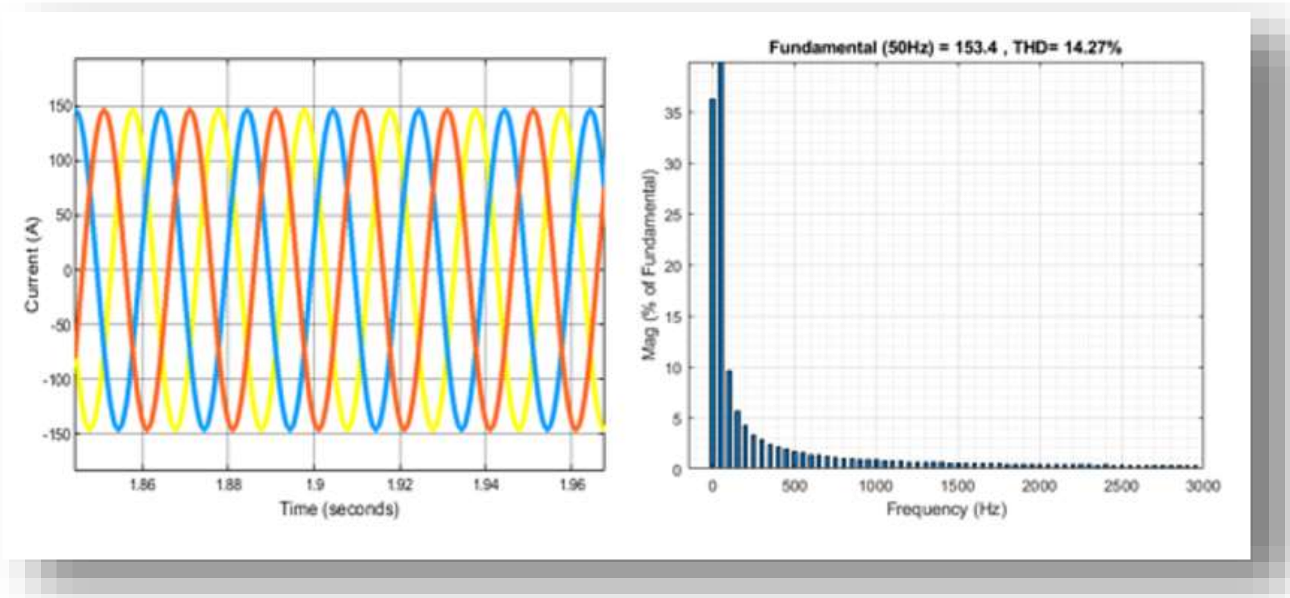


Figure 2: Current and ITHD at 0.5P with LCL-Filter

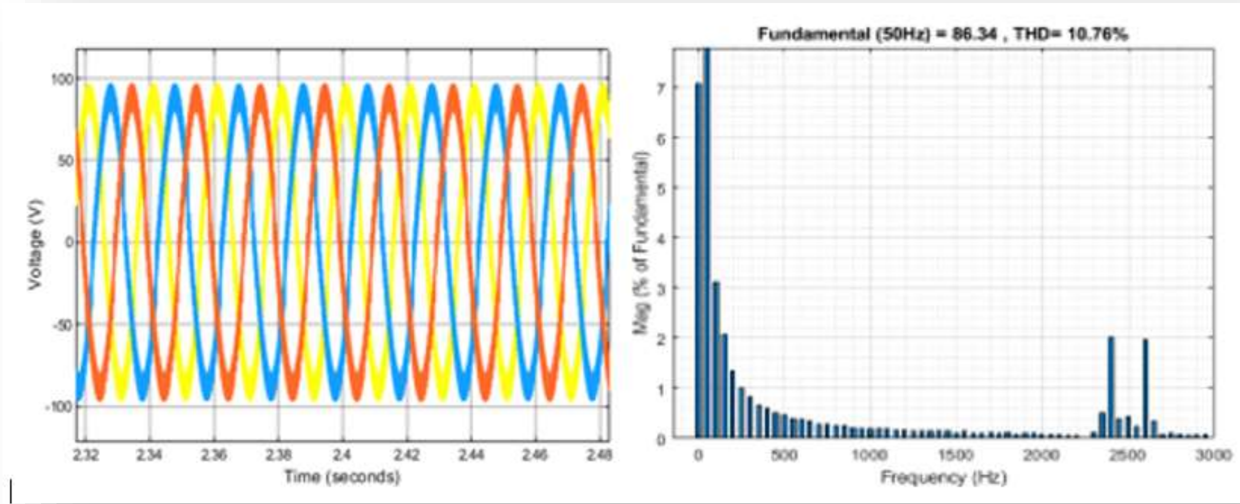


Figure 3: Voltage and ITHD at 2P with LCL-Filter

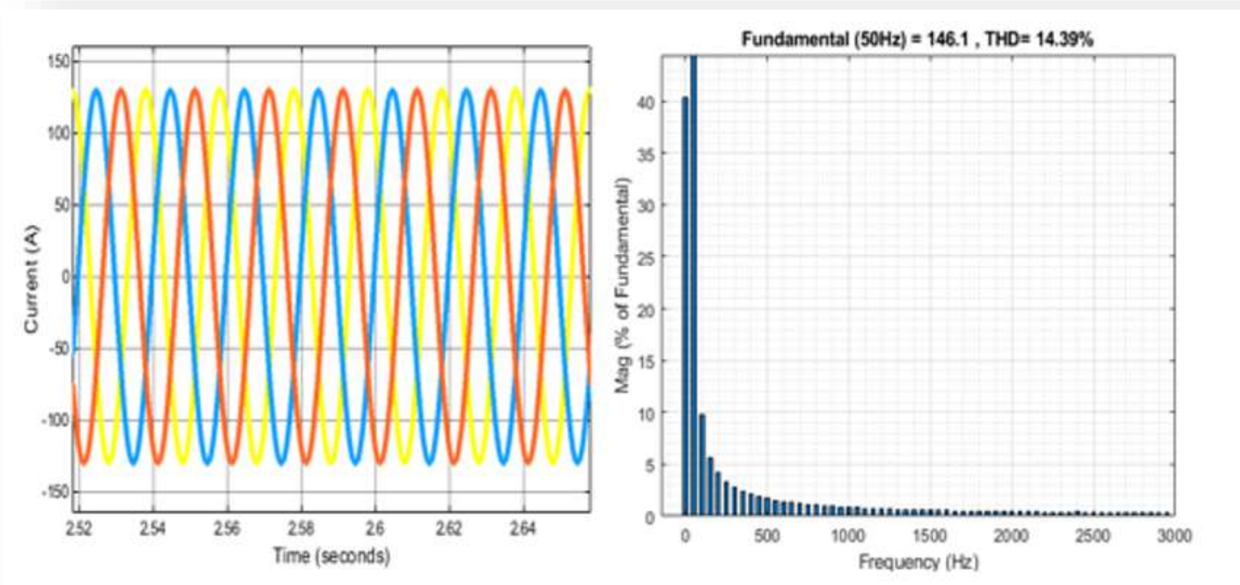


Figure 4: Current and ITHD at 2P with LCL-Filter

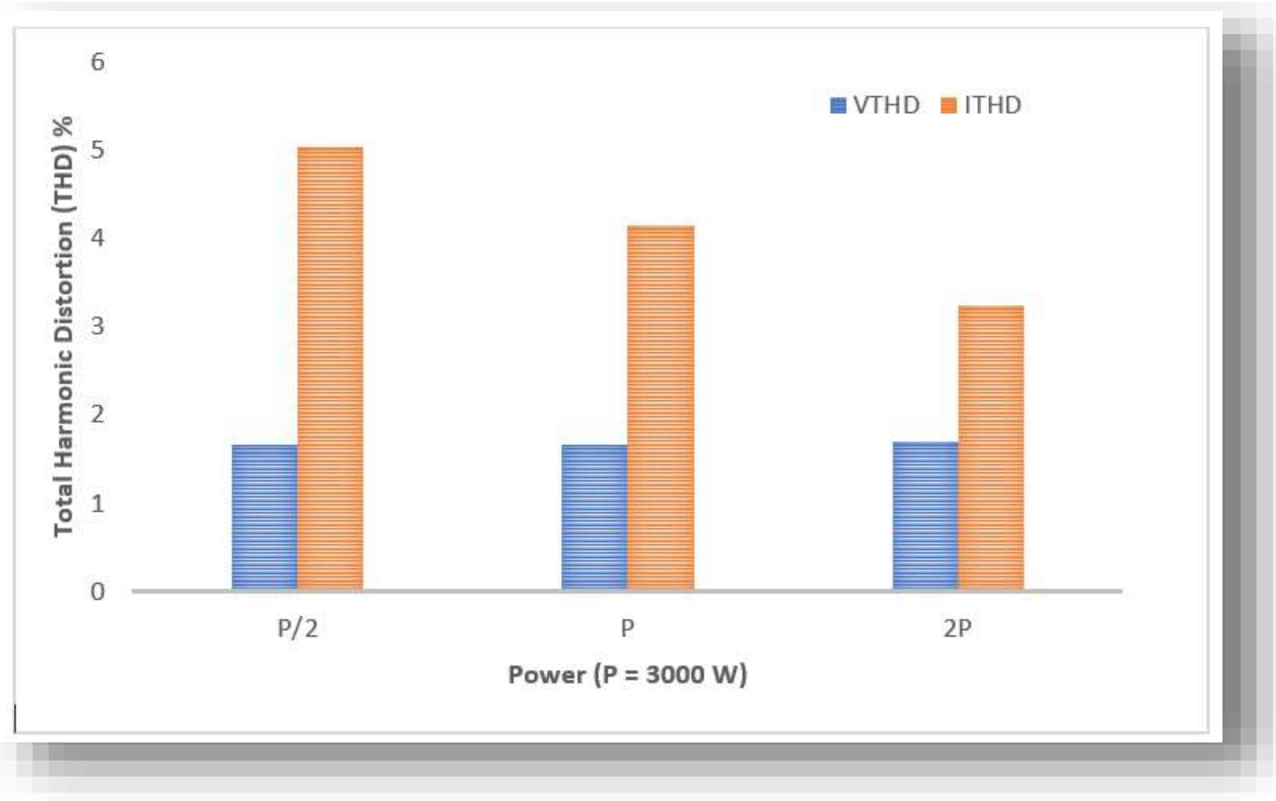


Figure 5: LCL Filter THD under Different Operating Power

## 5. CONCLUSION

This study investigated how varying photovoltaic (PV) operating power affects power quality, specifically voltage and current harmonic distortion, in a grid-connected low-voltage distribution system. Using a MATLAB/Simulink model of a 3 kW PV array interfaced via a voltage-source inverter with an LCL filter, harmonic performance was evaluated at different operating points. The simulation results demonstrate a clear dependence of harmonic emissions on inverter loading: operating the inverter at reduced power (0.5P) significantly increased current THD, while elevated operating levels (2P) produced markedly lower THD values. Quantitatively, raising operating power from 0.5P to 2P yielded an approximate 24% reduction in current THD at the point of common coupling, and voltage THD remained within IEEE Std 519 limits under higher loading conditions.

These findings confirm that inverter operating point and DC-link dynamics strongly influence PWM modulation quality and the resulting harmonic spectrum. The results underscore the importance of considering real operating conditions, not just steady-state rated operation, when assessing PV-integrated networks. In practice, maintaining inverters near optimal utilization, employing properly tuned LCL filtering, and adopting advanced control strategies (e.g., adaptive PWM, PR/repetitive control, or active/hybrid filters) can materially reduce harmonic injections and improve compliance with PQ standards.

The study is limited by its simulation scope: a single 3 kW system, an idealized grid model, and a finite set of operating scenarios. Interactions among multiple distributed inverters, site-specific grid impedance, dynamic irradiance profiles, and hardware non-idealities were not exhaustively modeled. Accordingly, the conclusions should be validated with extended simulations covering diverse feeder topologies and with experimental field measurements at higher penetration levels.

Future work should expand to multi-inverter feeders, including stochastic irradiance and load profiles, and evaluate the performance of adaptive control and AI-based harmonic mitigation under real-world conditions. Additionally, experimental validation on laboratory testbeds or pilot distribution feeders will be essential to translate these simulation insights into practical guidelines for utilities, inverter manufacturers, and standards bodies. Collectively, these steps will help ensure reliable, low-harmonic integration of PV generation into modern distribution networks.

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