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Analyzing Harmonic Reduction in Grid-Connected PV Systems through LCL Filtering Techniques

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Abstract: As the integration of photovoltaic (PV) systems into power grids increases, effectively managing harmonic distortion becomes essential for ensuring power quality and system reliability. This study examines the performance of L and LCL filters in reducing harmonic distortion in a grid-connected PV system, focusing on their impact under different loading conditions. A comprehensive simulation was conducted using a 3 MW PV system connected to a 400 V, 50 Hz grid. The analysis involved three scenarios which are case A: an L filter with a linear load, case B: an L filter with a non-linear load and case C: an LCL filter with a non-linear load. The study found that non-linear loads significantly elevated harmonic distortion levels, with the THDI increasing from 7.56% (linear load) to 14.58% (non-linear load). However, the application of the LCL filter effectively reduced harmonic distortion, bringing THDI down to 7.02%. These findings highlight that while linear loads produce lower harmonic distortion, the LCL filter is more effective in maintaining power quality in systems subjected to non-linear loads.

Keywords: harmonics, LCL filter, grid-connected PV system, power quality

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1. INTRODUCTION

The growing population leads to a projected power demand increase of up to 45% by the end of 2035 [1]. Non-renewable energy sources such as oil, gas, and coal contribute to environmental pollution, despite fulfilling 75% of the global electrical demand [2]. The investigation into non-renewable resources results in deforestation, pollution, and various environmental challenges. These sources contribute to the emission of greenhouse gases [3]. Conversely, Renewable Energy Resources (RES) provides a reliable, environmentally friendly, and continuous energy supply. The renewable energy sources such as solar PV, biofuel, geothermal, biomass, hydro energy, and wind energy do not produce CO2 emissions[4, 5]. The worldwide transition to renewable energy sources has markedly enhanced the incorporation of photovoltaic (PV) systems into the electrical grid. Photovoltaic systems, recognized for their environmentally friendly and sustainable energy generation, have seen extensive implementation in residential and commercial domains. Nonetheless, the incorporation of these systems presents significant obstacles, especially regarding power quality and grid stability[6]. A significant concern linked to grid-connected PV systems is the harmonic distortion caused by power electronic devices, which can negatively impact the performance and reliability of the electrical grid [7].

Harmonics refer to voltage or current waveforms that occur at multiples of the fundamental frequency. They are frequently generated by non-linear loads and power electronic devices utilized in photovoltaic inverters. The widespread use of these devices in photovoltaic systems may result in heightened harmonic distortion, potentially compromising the overall efficiency of the power grid. Harmonics present significant challenges, as they can result in excessive heating of electrical equipment, diminish system efficiency, and cause malfunctions in sensitive devices. Consequently, addressing harmonic distortion is essential for maintaining the reliability and stability of grid-connected PV systems [8, 9].

A key approach utilized to mitigate harmonics in photovoltaic systems involves the implementation of passive filters. The L filter, fundamentally an inductive filter, stands out as one of the most straightforward and commonly employed solutions for this application. L filters demonstrate efficacy in reducing low-frequency harmonics; however, they frequently encounter challenges in mitigating high-frequency components, particularly in systems characterized by non-linear loads. Consequently, L filters might not achieve the necessary harmonic reduction in complex grid settings where higher-order harmonics are common. This observation is especially clear in photovoltaic systems linked to non-linear loads, where the Total Harmonic Distortion of current (THDi) is generally greater than in systems with linear loads [10].

In response to the constraints of L filters, the LCL filter has been developed as a more effective option. The LCL filter enhances the traditional L filter design by incorporating a capacitor and an extra inductor, resulting in improved attenuation of high-frequency harmonics. The integration of inductive and capacitive elements enables the LCL filter to diminish harmonic content with greater efficiency, especially in systems characterized by non-linear loads. A variety of studies have shown that LCL filters provide superior harmonic mitigation compared to L filters, establishing them as a favored option in grid-connected PV systems where maintaining power quality is crucial [11-13].

LCL is a third-order system, it was compared with the first-order L filter rather than a second-order LC or third-order LCC filter due to its prevalent application in grid-connected PV systems and its effectiveness in mitigating lower-order harmonics. The LCL filter is widely acknowledged as an optimal trade-off between complexity, cost, and performance, offering substantial harmonic attenuation while maintaining system stability. In contrast, LC filters are less commonly used due to their lower impedance at resonant frequencies, making them less effective in mitigating grid-side harmonics. LCC filters, on the other hand, introduce additional complexity and potential resonance issues that require active damping strategies.

This study examines the effectiveness of harmonic reduction in L and LCL filters within grid-connected photovoltaic systems, considering both linear and non-linear load scenarios. The findings are organized into three sections: L filter with linear load, L filter with non-linear load, and LCL filter with non-linear load. The analysis indicates that although the L filter functions satisfactorily with linear loads, its performance notably declines when faced with non-linear loads, leading to increased THDi. The LCL filter demonstrates enhanced harmonic mitigation under non-linear load conditions, resulting in a significant decrease in THDi. This enhancement highlights the significance of choosing suitable filtering methods to ensure power quality in grid-connected photovoltaic systems.

The approach encompasses simulation analysis alongside a comparison with the IEEE standard for validation purposes. The simulation analysis encompasses the design principles of LCL and L filters, mathematical modeling of harmonic attenuation, and simulation studies aimed at predicting performance outcomes[14-18]. Essential metrics like total harmonic distortion (THD) are utilized to evaluate the performance of the filters. This study compares the performance of two filtering methods, offering valuable insights into the effectiveness of LCL filters in mitigating harmonic distortion. It contributes to expanding knowledge aimed at improving power quality in renewable energy systems.

In summary, selecting the appropriate filtering technique is essential for influencing the overall effectiveness of grid-connected PV systems. This investigation has shown that although L filters perform well under linear load conditions, their efficacy diminishes when faced with non-linear loads. The LCL filter stands out due to its improved ability to attenuate harmonics, making it the optimal choice for minimizing THDi and achieving superior power quality in intricate load situations. As renewable energy systems continue to evolve, ensuring power quality through appropriate filtering techniques will remain a key priority for both scholars and industry professionals.

2. METHODOLOGY

2.1 IEEE regulation standard

The utilisation of electronic equipment in solar systems will impact the reported power quality issue. The incorporation of the PV system into the grid must comply with the relevant standards established by the utility service provider. Standards such as IEEE 1547, IEC 61727, EN IEC 61000-3-4, and IEEE 519-2014 pertain to power quality, islanding detection, and total harmonic distortion (THD)[19]. This is conducted to ascertain if the values of power quality parameters conform to the prescribed range.

The IEEE standard 519-2014 states that at the point of common coupling (PCC), the total harmonic distortion (THD) of voltage must not exceed 3% for individual harmonics and 5% for electrical circuits rated between 1-69kV, as illustrated in Table 1.PCC is described as the integration point of a solar system with the primary grid. IEEE 519-2014 recommends that the background voltage distortion of the system should be less than 2.5% prior to the integration of distributed resources like photovoltaics (PV). The table indicates that an individual harmonic value below 5% is permissible for bus voltage V at PCC under 1 kV, with total harmonic distortion (THD%) remaining below 8%. The maximum allowable injected current into the grid is regulated according to the rules set by the International Electrotechnical Commission (61000-3-4 1998), as indicated in Table 2.This individual harmonic distortion (IHD) value will be referenced throughout this work.

Table 1. IEEE 519-2014 Standard

Bus voltage V at PCC	Individual harmonic (%)	THD (%)
$V \leq 1.0$kV	5	8
1kV < $V \leq 69$kV	3	5
69kV<$V \leq 161$kV	1.5	2.5

Table 2. IEC (61000-3-4 1998)

Harmonic Order, N	Admissible harmonic current, $\frac{I_n}{I_1} * \%$
3	21.6
5	10.7
7	7.2
9	3.8
11	3.1
13	2.0

15	0.7
17	1.2
19	1.1

I_n = harmonic current component, I_1= rated fundamental current

2.2 Description of the model

A photovoltaic (PV) module functions as the main component for generating direct current (DC) electricity. This module is designed in compliance with the parameters mentioned in Table 3 of the datasheet. To create a photovoltaic (PV) system with a capacity of 3 megawatts (MW), the PV modules are arranged in both series and parallel configurations. This arrangement has 1300 parallel strings, each consisting of 11 series-connected modules. The system is tested on an 8-megawatt (MW) load, which includes both linear and non-linear loads. For the non-linear load, a diode bridge rectifier is used to represent the non-linearity, with a resistance (R) value of 0.01 ohms.

Table 3. PV Module Specifications

Parameter	Value
Maximum Power, P_{max}	213.15w
Cells per module (N_{Cell})	60
Open circuit voltage V_{oc} (V)	36.3V
Short-circuit current I_{sc} (A)	7.84A
Voltage at Pmax, V_{mpp}	29V
Current at Pmax, I_{mpp}	7.35A
Temperature coefficient of V_{oc}, K_{voc}	-0.306099(%/deg.C)

A PV array is formed by connecting several PV cells to make a PV module. The photovoltaic module can be configured in either series (Ns) or parallel (Np) arrangements. A link existed between the quantity of photovoltaic modules and the sun irradiation level of the PV system, which influenced the production of voltage and current, respectively [20].

2.3 LCL filter design

The LCL filter is considered one of the most efficient techniques for reducing harmonic distortion in grid-connected photovoltaic (PV) systems, especially under non-linear load situations. The design, which integrates both inductive and capacitive elements, allows superior attenuation of higher-order harmonics relative to more rudimentary filtering techniques such as the L filter. A capacitor situated between them enhances effectiveness in diminishing harmonic content, particularly at high frequencies often generated by power electronics in photovoltaic inverters.

When building an LCL filter, it is crucial to balance various fundamental parameters to attain maximum performance. The main goal is to decrease Total Harmonic Distortion (THD) while reducing the overall dimensions, expenses, and power losses linked to the filter. Inductance values on both the inverter and grid sides, filter capacitance, and resonance frequency must be carefully selected to guarantee efficient harmonic mitigation while preventing system instability. Furthermore, the design must have limiting devices to prevent potential resonance difficulties, which may result in oscillations and diminish power quality.

This section defines the design concepts and concerns for the implementation of an LCL filter in a grid-connected photovoltaic system. The design procedure involves determining the suitable inductance and capacitance values according to the system's operational parameters, including the resonance frequency and resonance angular frequency. Addressing these problems allows the LCL filter to substantially improve the overall power quality of the PV system, becoming an essential component in modern renewable energy systems. Here are the formulations relevant to the design of LCL filters:

$$Z_b = \frac{(E_n)^2}{P} \quad (1)$$

$$C_b = \frac{1}{\omega_g . Z_b} \quad (2)$$

$$I_{max} = \frac{p \; . \; \sqrt{2}}{3 \; . \; V_f} \quad (3)$$

Where E_n represents the effective voltage of one phase, P denotes active power, C_b signifies base capacitance, ω_g indicates grid angular velocity, Z_b refers to base impedance, and V_f is the filter voltage. If the rated current is permitted to vary by 10% for the design parameters, the values in (4) and (5) are derived.

$$\Delta I_{L\_max} = \%10. \; I_{max} \quad (4)$$

$$L_1 = \frac{V_{DC}}{6 \; . \; f_{sw} \; . \; \Delta I_{L\_max}} \quad (5)$$

L_1 represents the inductance on the inverter side, fsw denotes the switching frequency, and V_{DC} refers to the DC link voltage. The capacitor value is constrained by a power factor drop of less than 5% at the rated capacity. The capacitance value, attenuation factor, resonance value, and resonance frequency are specified by equations (6) and (9).

$$C_f = 0.05 \, . C_b \quad (6)$$

$$K_a = 20\% = 0.2 \; \gg attenuation \, factor$$

$$L_2 = \frac{\sqrt{\frac{1}{K_a^2}} + 1}{C_f \; . \; \omega_{sw}^2} \quad (7)$$

$$\omega_{res} = \sqrt{\frac{L_1 + \; L_2}{L_1 \, . \; L_2 \; . \; C_f}} \quad (8)$$

$$f_{res} = \frac{\omega_{res}}{2\pi} \quad (9)$$

Where C_f denotes filter capacitance, L_2 represents grid side inductance, ω_{res} signifies resonance angular velocity, and f_{res} indicates resonance frequency. To mitigate resonance issues in the filter, the resonance frequency must be established at half the switching frequency and ten times the grid frequency [10]. The switching frequency and grid frequency range are presented below.

$$10f_g < f_{res} < 0.5f_{sw}$$

To mitigate resonance and diminish a portion of the ripple at the switching frequency, a series resistor must be connected to the capacitor. The resistance of this resistor must not exceed one third of the filter capacitor's impedance at the specified resonance frequency. The calculation of resistor value is provided in (10).

$$R_f = \frac{1}{3\ .\ C_f\ .\ \omega_{res}} \quad (10)$$

Table 4 shown a parameter use in LCL filter to mitigate harmonics in the system.

Table 4. Parameter for LCL filter

Parameter for LCL filter	Value
Inductor 1, L_1	1.6×10^{-5}
Inductor 2, L_2	2.97×10^{-7}
Capacitor, C_f	9.36×10^{-3}
Resistor, R_f	1.17×10^{-2}

2.4 Test system configuration

Figure 1 illustrates that the system employs a basic L filter linked to a linear load. The L filter comprises an inductor arranged in series between the photovoltaic inverter and the grid. Linear loads, including resistive or inductive components, do not generate substantial non-linearities inside the system. The primary purpose of this setup was to establish a baseline harmonic distortion level without the complexities introduced by non-linear loads. The expected outcome for this setup is not much harmonic distortion, as linear loads generally do not produce harmonics, and the L filter efficiently mitigates high-frequency harmonics from the inverter switching.

The second design Figure 2 utilises a L filter, similar to the initial setup, but contains a non-linear load linked to the system. Non-linear loads, like rectifiers and electronic devices with switching components, generate substantial harmonic content inside the system. In this design, the L filter is solely responsible for attenuating the harmonics produced by both the inverter and the non-linear load. This configuration facilitates the evaluation of the L filter's efficacy in mitigating total harmonic distortion (THD) under conditions of harmonically rich load currents. This configuration's results quantify the limits of a L filter under non-linear situations.

In the final arrangement which is as shown in Figure 3, an LCL filter is integrated into the system alongside a non-linear load. The LCL filter comprises two inductors and a capacitor configured in a series-parallel pattern. This filter architecture surpasses the L filter, offering superior attenuation of high-frequency harmonics, especially when non-linear loads are present. The capacitor in the LCL filter mitigates switching ripple, while the supplementary inductor further reduces harmonics. This design seeks to illustrate the improved harmonic attenuation capacity of the LCL filter in a system characterised by substantial harmonic production from both the inverter and the non-linear load. The expected outcome is a significant decrease in THD relative to prior designs, confirming the efficacy of the LCL filter in ensuring grid compliance and mitigating harmonic distortion.

2.5 Case Study

As shown in Table 5 the case study is divided into three distinct scenarios to evaluate the effects of different filter types and load conditions on harmonic distortion and power quality in grid-connected photovoltaic (PV) systems. Each case considers a unique combination of filters and loads to explore how these factors influence the system's overall performance, particularly in terms of Total Harmonic Distortion (THD).

In case A, an L filter is used with a linear load. Linear loads, such as resistive or inductive devices, maintain a proportional relationship between current and voltage. As a result, they typically introduce minimal harmonic distortion. The L filter, which is the simplest filter type, is sufficient for controlling low-frequency harmonics in such systems. However, its effectiveness is limited when higher-order harmonics are present, though this is not a significant issue with linear loads.

Case B examines the performance of the same L filter when connected to a non-linear load. Non-linear loads, which include devices like power electronics, cause the current to deviate from a sinusoidal waveform, leading to significant harmonic distortion. In this scenario, the L filter struggles to effectively reduce the higher THD caused by the non-linear load, exposing the limitations of this basic filter in handling such conditions.

In case C, an LCL filter is introduced along with a non-linear load. The LCL filter is a more advanced design, consisting of an additional inductor and capacitor, which enhances its ability to attenuate higher-order harmonics. This case demonstrates the superior performance of the LCL filter, particularly in reducing the THD associated with non-linear loads. The inclusion of the LCL filter leads to improved power quality, making it more suitable for systems where non-linear loads are prevalent.

Through this comparative study, the effectiveness of LCL filters in minimizing harmonic distortion and improving power quality is highlighted, especially in challenging conditions involving non-linear loads. The analysis underscores the importance of selecting the appropriate filtering technique based on load characteristics to ensure optimal performance in grid-connected PV systems.

Table 5. Case Study on every case

Type of Case	Type of filter	Type of load
Case A	L	Linear load
Case B	L	Non-linear load
Case C	LCL	Non-linear load

3. RESULT AND DISCUSSION

3.1 THDV performance for every case

In the analysis of harmonic distortion for all three-test configuration such as L filter with linear load, L filter with non-linear load, and LCL filter with non-linear load. The total harmonic distortion in voltage (THDV) was observed to be consistent and within the acceptable threshold as shown in Figure 4. The standard limit for THDV, as per grid code regulations, is 8%, ensuring that the system does not introduce excessive harmonic content into the grid. For each configuration tested, the THDV values remained below this threshold, demonstrating the effectiveness of both L and LCL filters in maintaining grid quality.

While non-linear loads are known to introduce higher harmonic distortion, the results show that both the L filter and the more advanced LCL filter effectively managed to keep THDV within acceptable levels. This consistent outcome across different load types highlights the filters' ability to control harmonic distortion without exceeding regulatory limits. Furthermore, the LCL filter, designed for enhanced harmonic attenuation, did not show a significant difference in voltage harmonic reduction compared to the simpler L filter, reinforcing the conclusion that both filter types can perform well under varying load conditions while ensuring grid compliance.

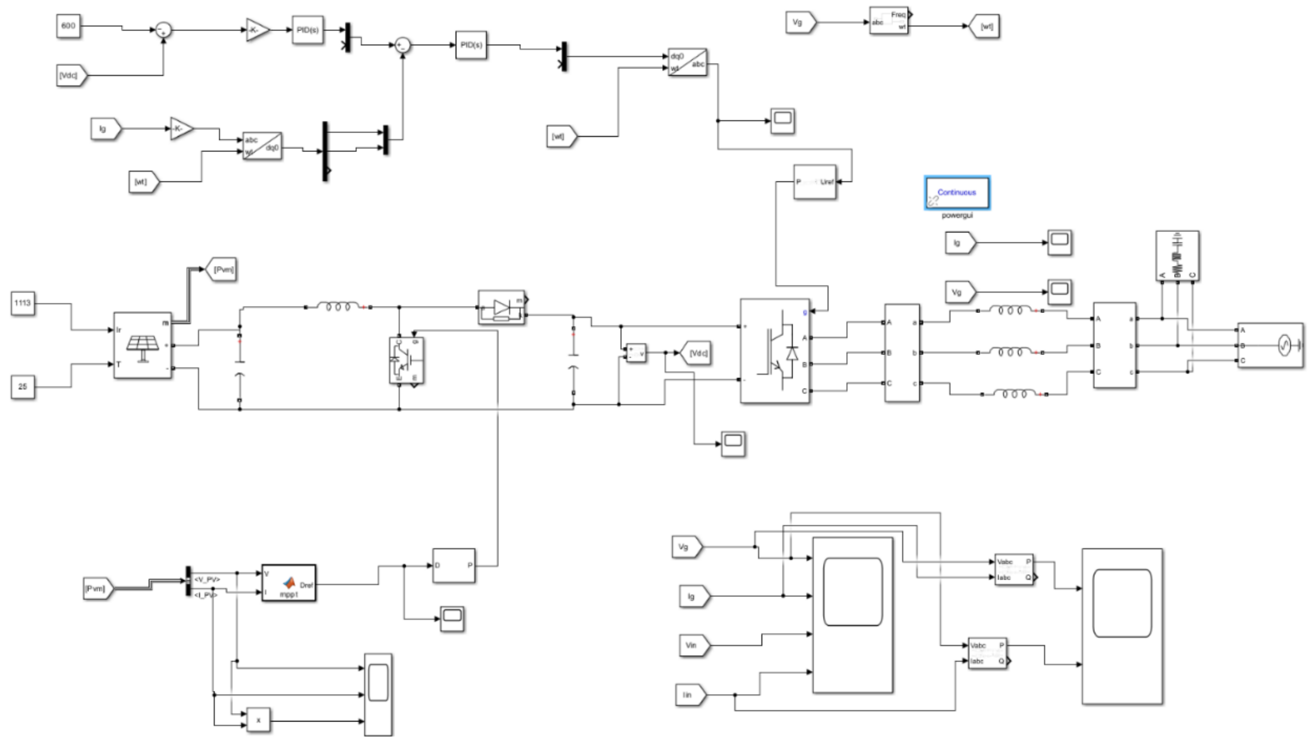

Figure 1. MATLAB model for L filter with linear load (Case A)

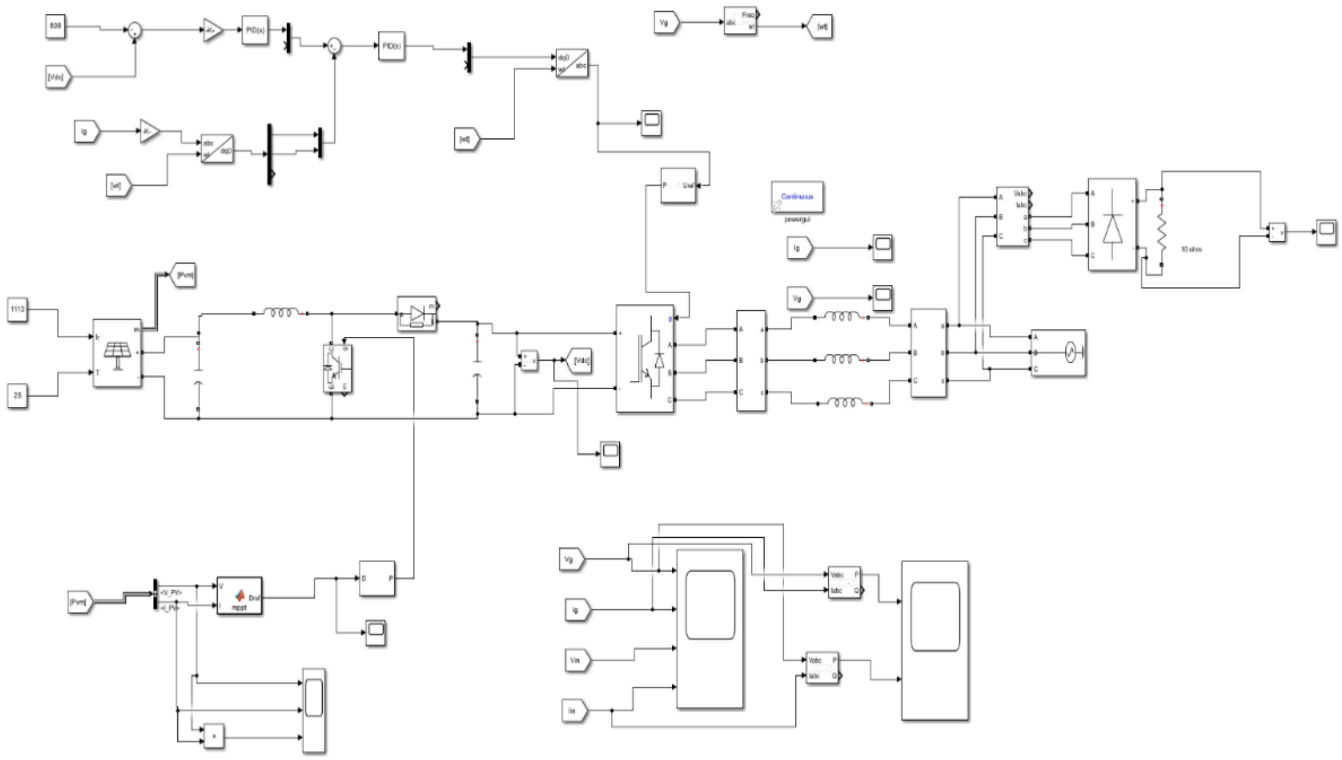

Figure 2. MATLAB model for L filter and non-linear load (Case B)

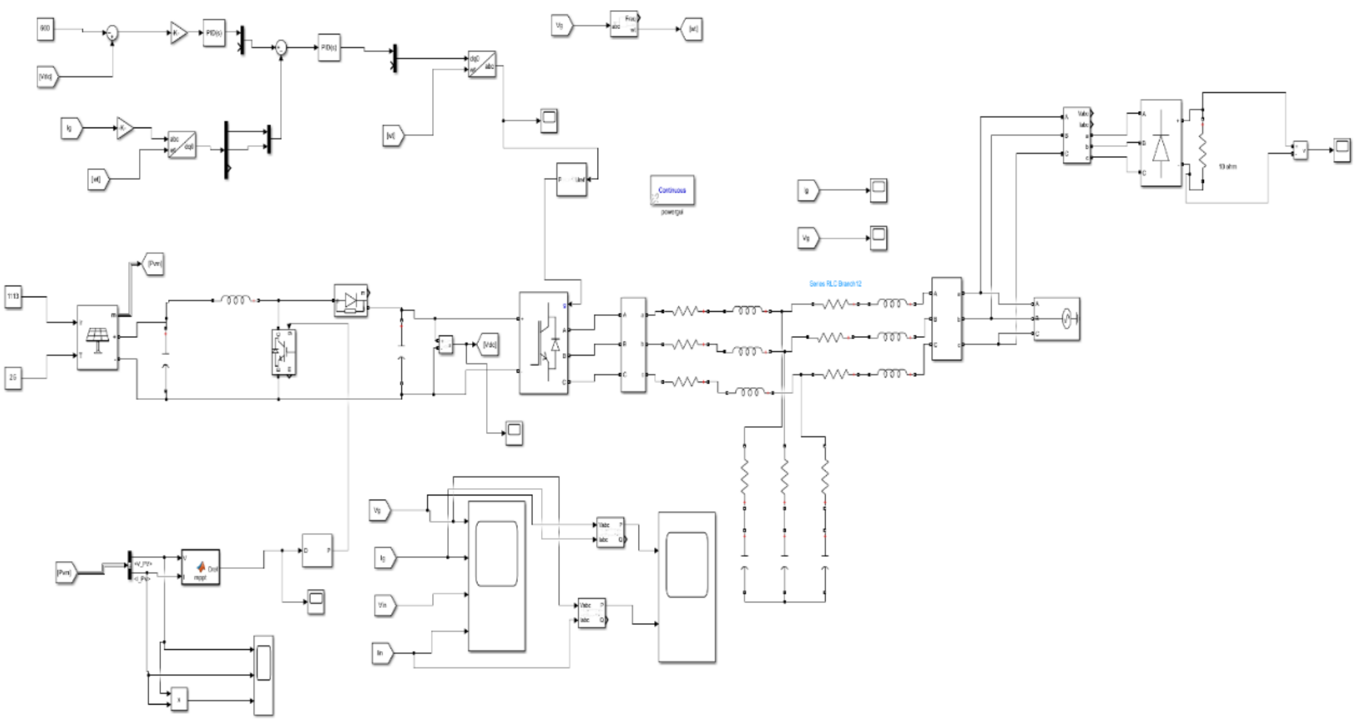

Figure 3. MATLAB model for LCL filter and non-linear load (Case C)

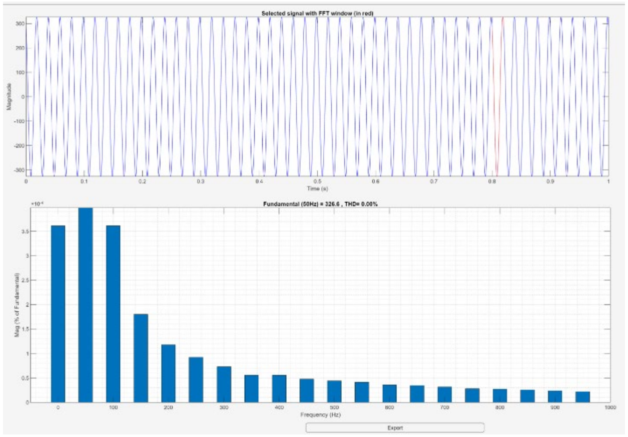

Figure 4. THDV simulation results

3.2 THDI performance for every case

In the analysis of the Total Harmonic Distortion in current (THDI) for the three test cases its focus shifts to examining the Individual Harmonic Distortion (IHD) to assess the harmonic levels in detail.

In the first case, where an L filter was used with a linear load, the THDI was measured at 7.56%. As shown in Figure 5, the individual harmonic levels were well controlled, with no significant peaks at higher-order harmonics. The low THDI indicates that the L filter effectively managed harmonic distortion in this setup, confirming that it performs well when working with linear loads where harmonic generation is naturally minimal.

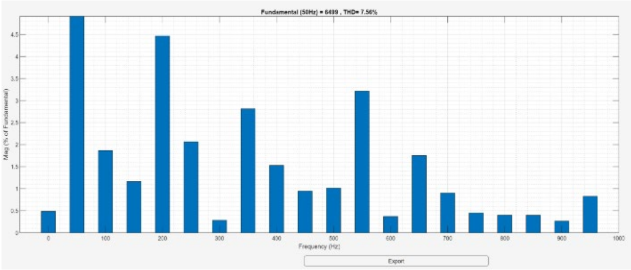

Figure 5. THDI for case A

In the second case, with an L filter and a non-linear load, the THDI increased significantly to 14.58%, as shown in Figure 6. The presence of lower-order harmonics, particularly the 3rd, 5th, and 7th harmonics, became much more prominent, resulting in higher IHD values. The L filter struggled to attenuate these harmonics, leading to a noticeable increase in distortion. The non-linear load introduced considerable harmonic content, demonstrating the limitations of the L filter when managing non-linear conditions.

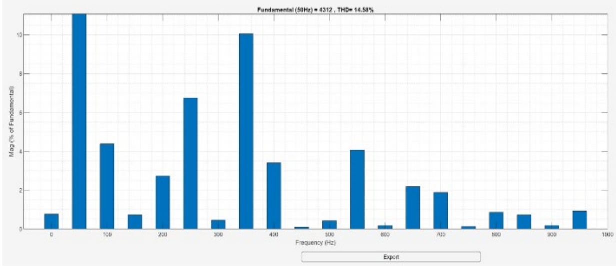

Figure 6. THDI for case B

In the third case, using an LCL filter with a non-linear load, the THDI dropped to 7.02%. As shown in Figure 7, the LCL filter significantly reduced both lower- and higher-order harmonics, leading to much lower IHD values across the frequency spectrum. The LCL filter's superior harmonic attenuation, demonstrating its effectiveness in reducing harmonic distortion under non-linear load conditions.

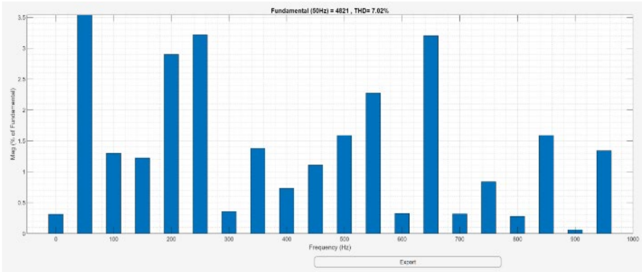

Figure 7. THDI for case C

Overall, as indicated by the figures and corresponding THDI values, the L filter performed adequately with linear loads with THDI of 7.56% but struggled with non-linear loads having THDI 14.58%. In contrast, the LCL filter with THDI of 7.02% was much more effective in controlling individual harmonic distortion, particularly in systems with non-linear loads, ensuring better compliance with harmonic standards.

3.3 Comparison individual Harmonics distortion (IHD) with the IEC standard

The analysis of harmonic distortion across various filtering techniques in grid-connected photovoltaic (PV) systems provides significant insights into their effectiveness in mitigating harmonics generated by both linear and non-linear loads. The results from the three cases examined reveal important differences in performance that merit further discussion.

In the first case, the implementation of an L filter with a linear load resulted in a Total Harmonic Distortion (THDI) of 7.56%. This relatively low THDI indicates that the L filter effectively minimizes harmonic distortion in scenarios where linear loads are predominant, as these loads typically generate fewer harmonics. The performance observed aligns with expectations, demonstrating the L filter's capability to maintain system integrity when subjected to minimal harmonic disturbances.

Conversely, the performance of the L filter deteriorated significantly when subjected to a non-linear load, leading to a much higher THDI of 14.58%. The data shown in Table 6 indicates that harmonics, particularly the 5th and 7th orders, were notably amplified, with the 7th harmonic reaching 10.05%, thus exceeding the IEC standard limits. This observation underscores the inadequacy of a simple L filter in environments where non-linear loads are prevalent. The findings suggest that reliance on L filters in such contexts may lead to compliance issues with harmonic standards, highlighting the need for alternative solutions.

In the third case, the application of an LCL filter in conjunction with a non-linear load showed a significant improvement in performance, reducing the THDI to 7.02%. This substantial reduction indicates that the LCL filter is more effective in mitigating low-order harmonics, particularly as shown in Table 6 the reduced contributions from the 5th (2.57%) and 7th (1.75%) harmonics. While the LCL filter demonstrates enhanced performance in addressing the issues posed by non-linear loads, it is noteworthy that some higher-order harmonics, such as the 13th and 19th, still exceed IEC standards. This suggests that while the LCL filter is an improvement over the L filter, it may not completely resolve high-order harmonic issues.

Table 6. Comparison of the results with the standard

Harmonic order	IHD Case A (%)	IHD Case B (%)	IHD Case C (%)	[IEC 61000-3-4:1998] Standard (%)
3	1.16	0.73	1.07	21.6
5	2.07	6.75	2.57	10.7
7	2.81	**10.05**	1.75	7.2
9	0.94	0.09	0.41	3.8
11	**3.21**	**4.06**	1.73	3.1
13	1.75	**2.18**	**3.91**	2.0
15	0.45	0.12	0.22	0.7
17	0.40	0.73	1.01	1.2
19	0.81	0.92	**1.69**	1.1
THDi	7.56	14.58	7.02	

4. CONCLUSION

In conclusion, the findings from this study emphasize the importance of selecting appropriate filtering techniques for harmonic mitigation in grid-connected PV systems. The results demonstrated that an L filter adequately managed harmonic distortion for linear loads, with a THDI of 7.56%. However, when subjected to non-linear loads, the L filter failed to effectively mitigate harmonics, resulting in a significantly higher THDI of 14.58%. In contrast, the LCL filter exhibited superior performance by reducing the THDI to 7.02%, demonstrating its effectiveness in suppressing harmonic distortions introduced by non-linear loads. These findings reinforce the necessity of implementing advanced filtering techniques like the LCL filter in PV-integrated systems to ensure compliance with power quality standards. Future research should explore further optimization of LCL filter parameters or hybrid filtering methods to enhance overall performance and mitigate high-frequency harmonics.

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