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Power Quality Enhancement of Grid Connected Solar Photovoltaic System Using LCL Filtre

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Abstract

The integration of renewable energy sources into the AC grid through power converters has significantly increased over the past two decades. To connect these power converters to the utility grid and address the high-order harmonics generated by the converter, an LCL filter is commonly deployed. Achieving high filtering performance that complies with strict grid code requirements while maintaining a balance between cost and efficiency necessitates an optimal LCL filter design. This paper introduces a modeling approach and a comprehensive design methodology for LCL filters in grid-connected converters, utilizing an analytical approach. Simulation results demonstrate that this method effectively mitigates 99% of current harmonics at the converter output.

Key Words: LCL Filter, Inverter, Grid connected, Passive damping, Photovoltaic systems

1. Introduction

The use of power converters for grid interconnection has seen a notable rise in applications such as power quality improvement, regenerative motor drives, and distributed generation. Distributed generation systems like photovoltaic (PV) panels and fuel cells typically produce energy in the form of DC voltage sources. Additionally, wind energy generates varying AC voltage which is often converted into DC as well. By utilizing DC/AC inverters, these DG systems can effectively transfer energy to the utility grid. However, the power electronic components employed in these voltage source inverters tend to introduce undesirable harmonics. These harmonics can disrupt nearby loads at the point of common coupling to the utility grid, potentially violating established standards for grid interconnection.

Therefore, to interface these power converters to the utility grid, a filter is often required to reduce harmonics in the output current to desirable limits [1]. LCL-filter is among the best performing filters for grid-connected voltage source inverters [3]. Design of filters used in grid-connected inverter applications involves a large number of constraints. The filter requirements are driven by tight tolerances of standards such as IEEE 519-1992–IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE 1547.2-2008–IEEE Application Guide for IEEE Standard, IEEE 1547-2005 – IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems [1-2-5], reactive power compensation limit and maximum allowable voltage drop across the filter to limit the switching losses [1-3]. IEEE Standard 519 establishes harmonic limits on voltage as 5% for total harmonic distortion (THD) Therefore, the common practice is to accept a maximum total harmonic distortion (THD) of 5% of rated inverter output.

Higher order LCL filters are essential to achieve these regulatory standard requirements at compact size and weight [1]. Higher order LCL filters are essential to achieve these regulatory standard requirements at compact size and weight [1]. The design of LCL filter parameters, including the grid-side and inverter-side inductors as well as the capacitor, typically requires an iterative process due to the interdependence between these parameters and the associated design criteria. As a result, the conventional procedure for designing an LCL filter is inherently complex and challenging. This paper, therefore, aims to introduce a simplified design approach for an LCL filter that fulfills regulatory requirements while also offering guidance on methodologies for achieving an optimized filter configuration.

2. System Modeling

This schematic illustrates the architecture of a grid-connected photovoltaic system. Solar energy, produced as direct current by the panels, is first conditioned by a DC/DC converter to optimize its extraction. It is then converted into alternating current via a voltage-source inverter, whose output is filtered by an LCL filter to reduce harmonics and improve power quality. A phase-locked loop (PLL) synchronizes the inverter voltage and frequency with those of the grid. The control system regulates the injected power, ensuring efficient energy transfer to the grid or to local loads [4].

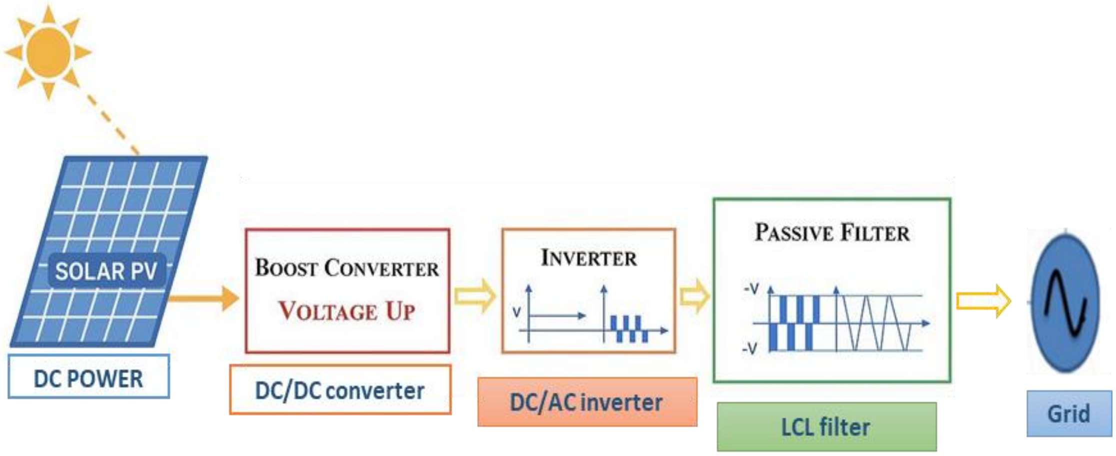

Figure 1: System block diagram with the LCL filter connected to the electrical network.

Source: Authors, (2025).

3. Modeling and Design of LCL Filter

3.1. Per Phase Model

Analysis and estimation approach of the L-C-L filter with damping resistance as seen in Fig.2 have been discussed in. The simplified formulae to estimate the parameters of the filter has stipulated in these literatures. The same approach will be used in this thesis to determine inverter side inductance, Li , grid side inductance, Lg , filter capacitance, c f and the damping resistance Rd .

The main function of the LCL filter is to reduce high-order harmonics on the output side; however poor design may cause a distortion increase. Therefore, the filter must be designed correctly and reasonably.

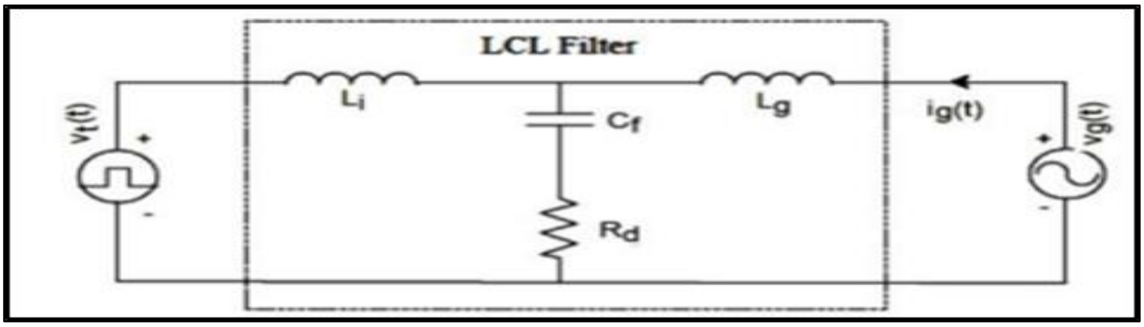

Figure 2: Single Phase equivalent circuit LCL.

Source: Authors, (2025).

4. Frequency Response and Transfer Function

An important transfer function is HLCL = ig/vi, where the grid voltage is assumed to be an ideal voltage source capable of dumping all the harmonic frequencies. If one sets vg = 0,

conditions for current-controlled inverters, the transfer function of the LCL filter (neglecting damping) is

$$\mathrm{H_{LCL}(s)} = \frac{1}{\mathrm{L_1C_fL_2s^3 + (L_1 + L_2)s}} \qquad (1)$$

and with some simple algebraic manipulations, the transfer function with damping resistance becomes

$$\mathrm{H_{LCL_d}(s)} = \frac{\mathrm{C_fR_fS + 1}}{\mathrm{L_1C_fL_2S^3 + C_f(L_1 + L_2)R_fS^3 + (L_1 + L_2)S}} \qquad (2)$$

5. Filter Design Procedure

Several characteristics must be considered in designing a LCL filter, such as current ripple, filter size and switching ripple attenuation. The reactive power requirements may cause a resonance of the capacitor interacting with the grid.

Therefore, passive or active damping must be added by including a resistor in series with the capacitor[6].

The following parameters are needed for the filter design: $\mathrm{E_n}$-line to line RMS voltage (inverter output), $\mathrm{V_{ph}}$ -phase voltage (inverter output), $\mathrm{P_n}$ - rated active power, $\mathrm{V_{DC}}$-DC bus voltage, $\mathrm{f_g}$-grid frequency, $\mathrm{f_{sw}}$-switching frequency, $\mathrm{f_{res}}$- resonance frequency.

The first step in calculating the filter components is the design of the inverter side inductance Li , which can limit the output current ripple by up to 10% of the nominal amplitude. It can be calculated according to the equation derived in [7]:

$$\mathrm{L_i} = \frac{\mathrm{V_{DC}}}{\mathrm{6f_{SW} \times \Delta I_{L-max}}} \qquad (3)$$

Where $\mathrm{\Delta I_{L-max}}$ is the 10 % current ripple specified by:

$$\mathrm{\Delta I_{L-max}} = 0.1\frac{\mathrm{P_n}\sqrt{2}}{\mathrm{3U_n}} \qquad (4)$$

For the design of the filter capacitance, it is considered that the maximum power factor variation seen by the grid is 5%, indicating that the base impedance of the system is adjusted as follows:

$$\mathrm{C_f} = 0.05 \times \mathrm{C_b} \qquad (5)$$

A design factor higher than 5% can be used, when it is necessary to compensate the inductive reactance of the filter.

The LCL filter should reduce the expected current ripple to 20%, resulting in a ripple value of 2% of the output current [2].

In order to calculate the ripple reduction, the LCL filter equivalent circuit is initially analyzed considering the inverter as a current source for each harmonic frequency in accordance with Fig. 1. Equations (6) and (7) relate the harmonic current generated by the inverter with the one injected in the grid.

$$\frac{i_g(h)}{i_i(h)} = K_a \qquad (6)$$

And

$$L_2 = \frac{\sqrt{\frac{1}{K_a^2}+1}}{C_f \times f_{sw}^2} \qquad (7)$$

A resistor in series (R_f) with the capacitor attenuates part of the ripple on the switching frequency in order to avoid the resonance. The value of this resistor should be one third of the impedance of the filter capacitor at the resonant frequency [6], and the resistor in series with the filter capacitance is given by:

$$R_f = \frac{1}{3f_{res}C_f} \qquad (8)$$

The resonant frequency range must be considered to satisfy,

$$f_{res} = \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}} \qquad (9)$$

$$10f_g < f_{res} < 0.5f_{sw} \qquad (10)$$

After defining all parameters for LCL filter two configuration are possible for implementation. Parameters defined in Section A are valid for wye capacitors connection, however using simple and well known wye delta transformation for balanced system wye configuration can be transformed to delta [8].

It's obvious from (11), that for delta configuration size of capacitor should be three times smaller than for wye configuration and vice versa for damping resistance:

$$R_{f_\Delta} = 3R_{f_Y} \qquad (11)$$

$$C_{f_\Delta} = \frac{C_{f_Y}}{3} \qquad (12)$$

Grounding the neutral, or central point of a wye connection, is a common practice [9], often required by the U.S. National Electrical Code (NFPA-70). This grounding plays a crucial role in stabilizing and controlling voltages relative to ground, making the system less vulnerable to voltage spikes and faults that could result in elevated ground voltages. On the other hand, delta configurations generally do not present challenges or uncertainties related to grounding. For this reason, the authors recommend the delta connection as a simpler, more reliable alternative for achieving effective performance in an LCL filter system[10].

6. Filter Design Used

A step by step procedure to obtain parameters of the filter with wye configuration considering the following given data, needed for the filter design: $E_n = 120\sqrt{3}$V –line RMS voltage, $P_n = 5$kW-rated active power, $f_{sw} = 15$kHz-switching frequency, $K_a = 0.2$-attenuation factor, $f_g = 2\pi 50$-grid frequency (parameters are shown in Table 1).

Table 1: Design System Parameters.

Parameter		Value
$\mathbf{f_g}$	Grid frequency	50 Hz
$\mathbf{f_{sw}}$	PWM carrier frequency	15 kHz
$\mathbf{V_g}$	Phase grid voltage	120
$\mathbf{V_{DC}}$	DC link Voltage	400
$\mathbf{L_i}$	Inverter side inductor	2.8 mH
$\mathbf{L_g}$	Grid side inducto	1.3 mH
$\mathbf{C_f}$	Capacitor filter Y/∇	92.4 µF
$\mathbf{R_f}$	Damping Resistor Y/∇	1.97 Ω

Source: Authors, (2025).

7. Simulation Results And Discussions

Models for LCL filter evaluation have been analyzed using MATLAB and Simulink Power System ToolBox simulation environment, Fig 3 shows the Simulink model of the system with the LCL filter. Here, the design parameters as shown in Table 1 was used to develop a Simulink model to carry out performance analysis on the LCL filter.

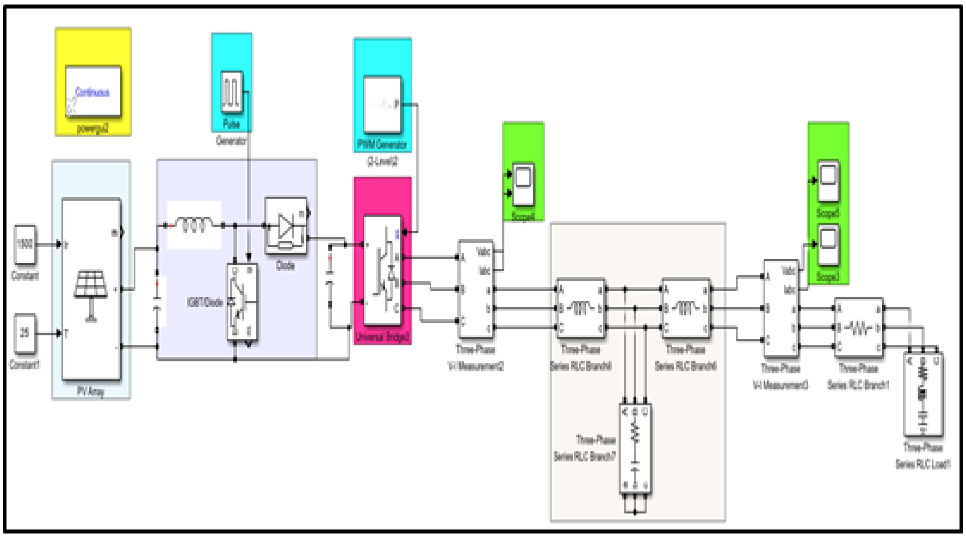

Figure 3: System Considered Designed in Matlab Simulink

Source: Authors, (2025).

8. Frequency Plots for Damped and Undamped LCL Filter

The Bode plots of the LCL filter without and with damping are shown in Fig. 4. The insertion of a series resistance with the capacitor eliminates the gain spike, smoothing the overall response and rolling-off to -90° degrees for high frequency, instead of -180° degrees. The LCL filter can achieve high performance at high frequency with an attenuation rate of -60 d B/decade.

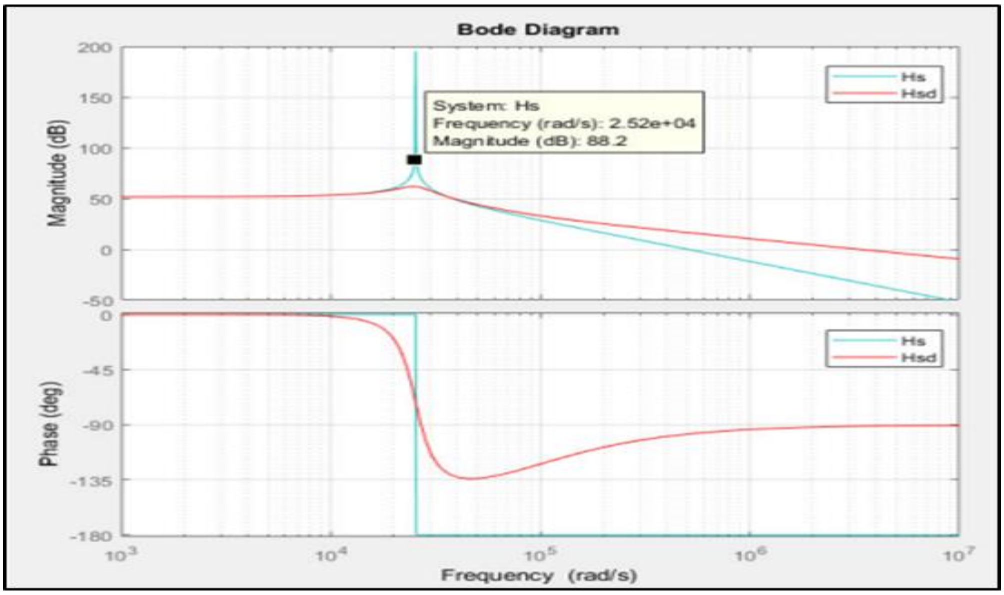

Figure 4: Bode plot for damped and undamped LCL filters

Source: Authors, (2025).

9. Harmonics Before Filtering in the System

This section discusses the harmonic characteristics of the unfiltered photovoltaic (PV) inverter system. The analysis encompasses both the current and voltage waveform and its frequency spectrum evaluated through Fast Fourier Transform (FFT). Examination of Figure 5,6 reveals that the voltage waveform significantly deviates from an ideal sinusoidal form, primarily due to the substantial presence of harmonic distortions. Further insight is provided by Figure 7, which illustrates the FFT analysis, indicating that the system's Total Harmonic Distortion (THD) reaches an elevated level of 88.08%. This magnitude of THD renders the system incompatible with grid-connected applications, as utility standards typically mandate a THD of less than 5% for such systems.

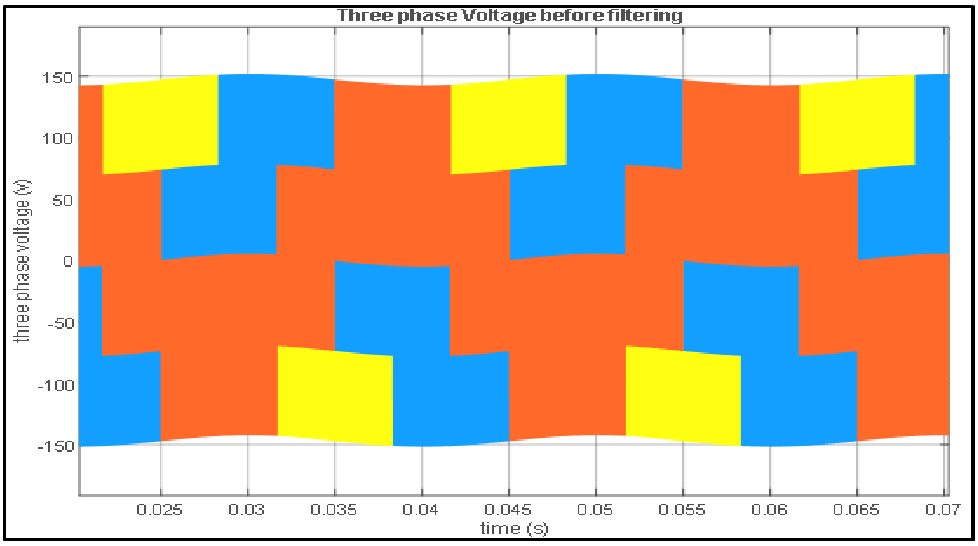

Figure 5: three phase voltages before filtering.

Source: Authors, (2025).

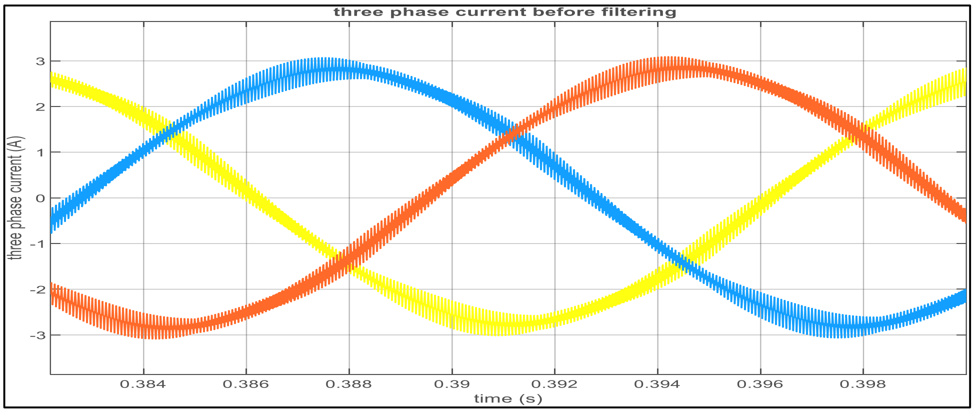

Figure 6: three phase currents before filtering.

Source: Authors, (2025).

The FFT settings are as followed: the start time of 0.4 seconds, number of cycles 15, fundamental frequency of 50 Hz, max frequency of 1000 Hz, max frequency for THD computation is Nyquist frequency. The result as shown on Fig.7.

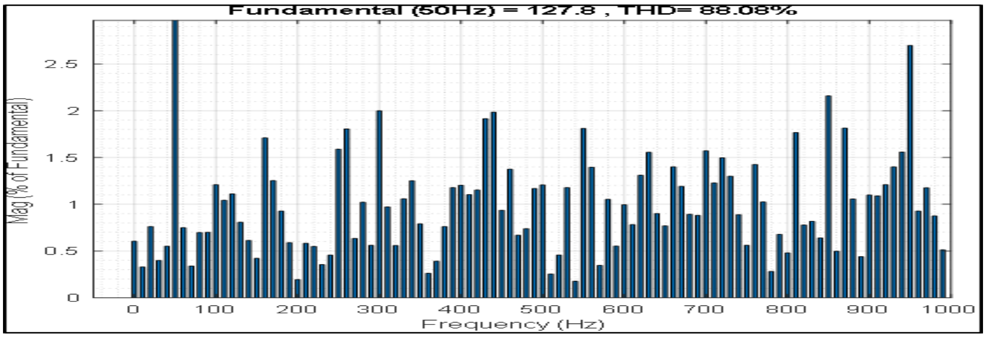

Figure 7: THD analysis before filtering.

Source: Authors, (2025).

10. Harmonics After Filtering in The System

We put another scope just after the LCL filters to evaluate the diminution of THD generated by the inverter after filtering. The Fig.8, 9 shows the three phase waves of voltages and currents.

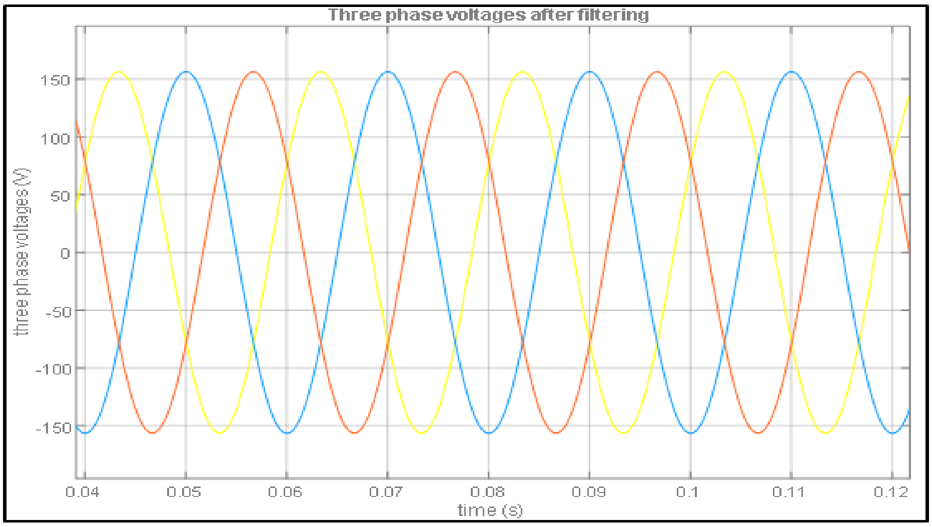

Figure 8: three phase currents after filtering.

Source: Authors, (2025).

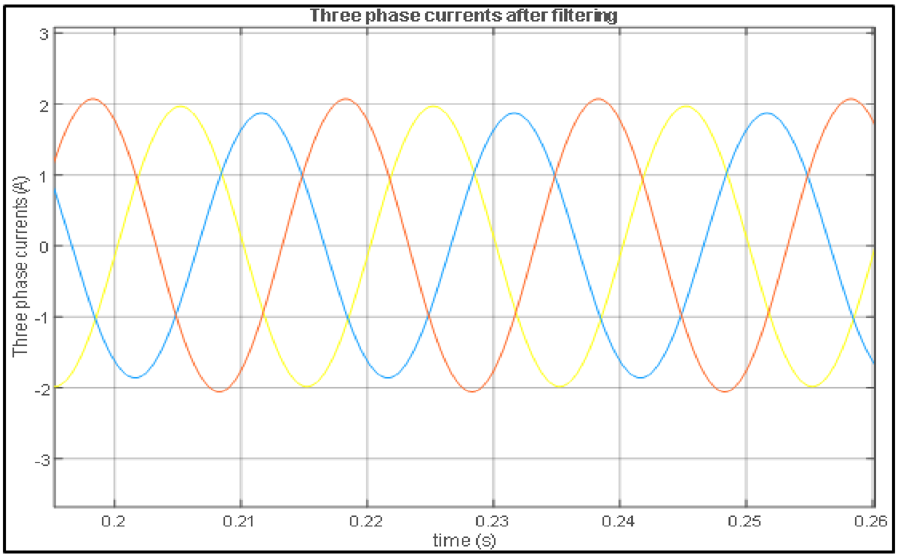

Figure 9: three phase currents after filtering.

Source: Authors, (2025).

The FFT settings are as followed : the start time of 0.4 seconds, number of cycles 15 , fundamental frequency of 50 Hz, max frequency of 1000 Hz, max frequency for THD computation is Nyquist frequency. The result as shown on Fig.10

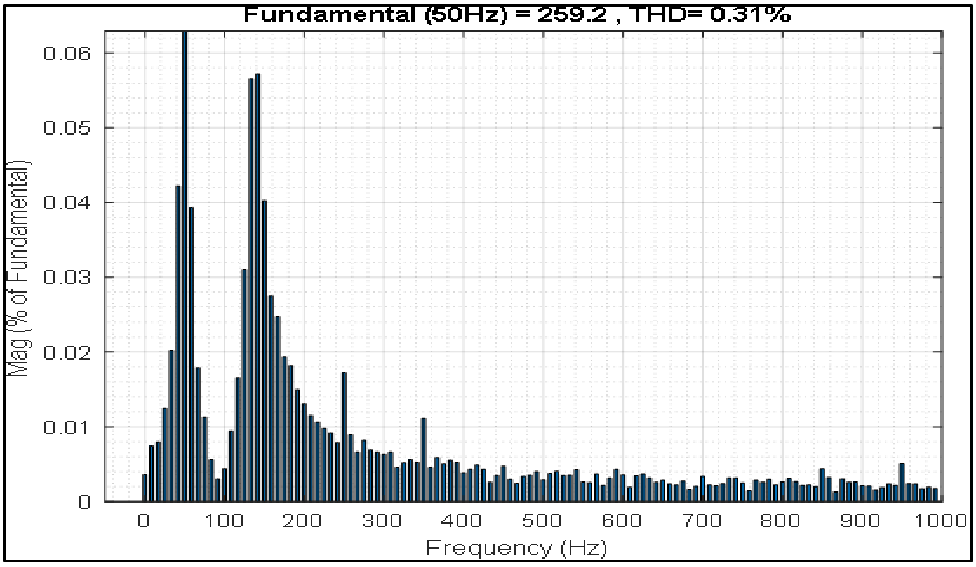

Figure 10: THD analysis after filtering.

Source: Authors, (2025).

Fig. 8, 9 shows the output current and voltage waveform of the inverter system with the LCL filter. Here, it is seen that the waveforms are all sinusoidal at this point since a greater percentage of the harmonics present at the output of the PV system has been filtered out by the welldesigned LCL filter. The harmonic content has also been reduced from 88.08% to 0.31%. However, Fig.10 reveals that the LCL filter cannot optimally handle the low order harmonics.

11. Conclusions

This article presents an innovative, robust, and systematic design methodology for the development of an LCL filter used as an interface between a three-phase power converter and the electrical grid. This type of filter plays a crucial role in mitigating switching-frequency current harmonics generated by the converter. The proposed methodology stands out for its simplicity and efficiency, while meeting the requirements imposed by grid codes. Unlike traditional approaches, which are often complex, this method is straightforward and simplified. It incorporates four fundamental design criteria, including compliance with limits set for reactive power.

The filter parameters determined using this methodology were examined with MATLAB-Simulink software. The simulation results clearly demonstrate the reliability, relevance, and optimal filtering performance of the proposed solution. These simulations reveal an exceptional harmonic attenuation capability, achieving a reduction of over 99.51% in current harmonics at the converter output. This performance significantly exceeds the thresholds set by IEEE 519, which states that total harmonic distortion (THD) must remain below 5%.

As a result, this design methodology proves to be fully compliant with industrial standards. The practical implications of this study are considerable, as it paves the way for large-scale and seamless integration of renewable energy sources into electrical grids.

Author's Contribution

Conceptualization: Mohammed Kaouka, Hakim Azizi and Abdelhadi Hameurlaine.

Methodology: Mohammed Kaouka and Hakim Azizi.

Investigation: Mohammed Kaouka and Hakim Azizi.

Discussion of results: Mohammed Kaouka, Hakim Azizi and Abdelhadi Hameurlaine.

Writing – Original Draft: Mohammed Kaouka.

Writing – Review and Editing: Mohammed Kaouka and Hakim Azizi.

Resources: Hakim Azizi.

Supervision: Hakim Azizi and Abdelhadi Hameurlaine.

Approval of the final text: Mohammed Kaouka, Hakim Azizi and Abdelhadi Hameurlaine.

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References:

[1] John V, Channegowda PB, Mukherjee N, Krishnan A, Karanth A. Optimization of Higher Order Filters for Grid Connected High Frequency Power Converters, Department of Electrical Engineering, IISc Bangalore; 2009.

[2] Yitao L, Jianchun P, Guibin W, Huaizhi W, Kye YS. LCL Filter Design and Analysis of Grid-Connected Converter for Power Quality and EMI Compliance, 7th Asia Pacific International Symposium on Electromagnetic Compatibility. 2016;142 – 144.

[3] Reznik A, Godoy Simoes M, Al-Durra A, Muyeen SM. LCL Filter Design and Performance Analysis for Grid Interconnected Systems, IEEE Transactions on Industry Applications. 2014;50(2):1225 – 1232.

[4] J. C. Das, "Harmonic Distortion Limits According to Standards," in Power System Harmonics and Passive Filter Designs, IEEE, 2015, pp.427-451.

[5] Ben Said-Romdhane M, Naouar MW, Belkhodja IS, Monmasson E. An Improved LCL Filter Design in Order to Ensure Stability without Damping and Despite Large Grid Impedance Variations, Energies. 2017;10:336.

[6] 142-2007 - IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, IEEE Std 142-2007, 2007.

[7] M. Baghdadi, E. Elwarraki, N. Mijlad and I.A. Ayad, "SIMSCAPE Electrical Modelling of the IGBT with Parameter Optimization Using Genetic Algorithm", in Journal of Electrical and Computer Engineering, vol. 2021, Article ID 6665384, 11 pages, 2021.

[8] Bai Baodong and Chen Dezhi, "Inverter IGBT loss analysis and calculation," in IEEE International Conference on Industrial Technology (ICIT), pp. 563-569.

[9] MASSAWE. Henry, «Grid Connected Photovoltaic Systems with Smart Grid functionality». Mémoire de master, Norwegian University of Science and Technology, June 2013.

[10] M. Liserre, F. Blaabjerg and S. Hansen, 'Design and Control of an LCL-Filter-Based Three-Phase Active Rectifier', IEEE Transactions on Industry Applications, Vol. 41, N°5, pp. 1281 – 1291, 2005.