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Hybrid passive damping filter of single-phase grid-tied PV-micro inverter

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ABSTRACT

Photovoltaic (PV) microinverter with inductor-capacitor-inductor (LCL) filter has many advantages, but it has resonance with the grid current situation could potentially lead to stability issues to enhance the power quality; reducing the grid current total harmonic distortion (THD) is crucial, as it currently exceeds the limits set by the IEEE power system standards. That improves the hybrid passive damping filter topology, which can perform better than the LCL output filter. The damping filter is effective in alleviating the resonance peak occurring at the resonant frequency of the LCL filter, thereby minimizing voltage overshoots and ringing; by utilizing smaller capacitors, the damping filter enhances system reliability while also reducing the cost and size of the LCL filter. Simulation research has been done to propose a hybrid passive damping filter using MATLAB/Simulink tools under both conditions, the steady-state and dynamic response. Simulation results indicate that the passive damping filter works well under both conditions with low THD compared to LCL and H-Bridge (H-B) filters. Many methods are used to solve the problem of high THD grid current. The passive damping filter method simplifies the PV microinverter. This study aims to achieve a high-efficiency PV microinverter by minimizing total power losses.

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1. INTRODUCTION

The supply of non-renewable energy sources like coal and oil is dwindling due to their finite availability and the rising electricity demand [1], [2]. As a result, users need to transition to renewable energy sources like solar energy. Energy is the foundation of modern society, powering myriad activities essential for daily life. However, as global energy demands continue to rise, concerns about environmental Sustainability and resource depletion have prompted a shift toward sustainable and renewable energy sources [3]. The Seventh Sustainable Development Goal (SDG 7) is focused on ensuring universal access to affordable, reliable, sustainable, and modern energy. This goal underscores the importance of transitioning to energy systems that support economic growth and development while minimizing environmental impact [4].

Additional indicators highlight the focus on increasing the proportion of renewable energy and improving energy efficiency. The main goals are to offer cost-effective and dependable energy access while increasing the global proportion of renewable energy sources. These objectives additionally highlight the enhancement of energy efficiency, the advancement of international cooperation, and investment in clean energy infrastructure.

Among these sources, solar energy is distinguished by its abundance, offering the potential to meet a huge portion of energy needs. Solar energy, recognized as one of the most plentiful renewable resources, is captured through photovoltaic (PV) systems. These systems consist of solar panels made of semiconductor materials that capture sunlight and transform it directly into electricity via the photovoltaic effect. PV inverters are crucial components in solar energy systems that are usable by household appliances and suitable for the electrical grid. PV inverters are crucial components of solar energy systems. They transform the direct current produced by solar panels into alternating current, enabling seamless integration with the electrical grid.

Additionally, they ensure that the electricity generated aligns with the grid’s frequency and voltage. PV inverters are equipped with features like maximum power point tracking (MPPT), which optimizes the power output from solar panels by continually adjusting their performance to adapt to changing environmental conditions [5]. Beyond their core conversion function, PV inverters are vital in solar energy systems' overall management and safety. They monitor the system’s performance, detect faults or any drop in efficiency, and can disconnect the system in case of grid failures or other electrical issues, ensuring safety and durability. Advanced PV inverters also offer features like real-time monitoring and integration with smart grid technology, improving the efficiency and management of solar power systems.

PV string inverters are frequently utilized in small to medium-sized solar installations, where several solar panels are connected in string, and their combined DC output is fed into a single inverter. This type of inverter is cost-effective and simple to install. It makes a popular option for small solar systems [6]. String inverters are installed at a central location, typically close to the main electric service panel. In these systems, the panels' collected (DC) power is transformed into (AC) power. One of the drawbacks of string inverters is that the weakest panel within it influences the performance of the entire string [7]. For instance, if one panel is shaded, it can significantly diminish the overall output. However, modern string inverters often incorporate multiple MPPTs to help mitigate this issue to some extent by optimizing groups of panels separately. Despite these limitations, string inverters remain a reliable and efficient solution for many solar installations, providing a good balance between cost and performance.

PV-microinverter represents a more recent advancement in solar technology, offering several advantages over traditional. Unlike string inverters, microinverters are installed on each solar panel, allowing for the conversion of DC to AC current at each panel [8]. This setup allows each panel to operate autonomously, improving the system efficiency because the performance of one panel is not affected by shading on another [9]. That makes microinverters particularly beneficial in installations where shading, odd roof angles, or variable light conditions are present. Microinverters also provide enhanced system monitoring and troubleshooting capabilities as they allow for panel-level data collection and analytics [10]. This level of detail helps identify underperforming panels quickly, making maintenance and optimization more straightforward.

Additionally, by reducing the system’s DC voltage, microinverters increase the safety of the solar installation. The main drawback of micro inverters has historically been their higher initial cost compared with string inverters, but as technology has advanced, this cost gap has been narrowing. One-stage PV microinverters perform the DC-to-AC conversion process directly in a single step [11]. This straightforward approach simplifies the conversion process and can offer advantages in terms of efficiency and reliability because fewer components can fail. The simplicity of the one-stage conversion process ensures that electrical losses are minimized, potentially boosting the overall energy output from the solar panels [12]–[14].

However, one-stage PV microinverters may be limited in handling wide variations in input voltage, which can occur due to changes in sunlight throughout the day. That can impact their effectiveness in environments with highly variable sunlight or shading. Despite this limitation, one-stage microinverters are appreciated for their efficiency and are good for installations with consistent sunlight and minimal shading [15].

Two-stage PV microinverters address some of the limitations found in one-stage models by adding an intermediate step in the conversion process [16]. In a two-stage system, the initial phase generally focuses on conversion. The first stage converts the variable DC voltage produced by the solar panel into a stable DC voltage, while the second stage transforms this stable DC voltage into alternating current (AC). This additional step allows the microinverter to handle a wider range of input voltages more effectively and maintain optimal performance even under fluctuating sunlight conditions. The two-stage approach can improve the overall efficiency and adaptability of the PV microinverter, particularly in installations with variable shading or changing weather conditions.

Although this added complexity can increase the cost and the number of components that could potentially fail, the benefits of more reliable and efficient power conversion often mitigate these concerns. Two-stage PV microinverters are particularly beneficial in settings where maintaining high efficiency across diverse conditions is essential for optimizing energy production. The quadratic boost converter is a cutting-edge power electronics component that optimizes the voltage conversion process in solar systems. It efficiently boosts the DC voltage output of solar panels to the necessary levels for grid integration. This technology minimizes energy losses and maximizes the system's energy output [17].

The LCL output filter is a crucial component that ensures the quality of the electricity fed into the grid. It reduces THD and filters out noise from the AC output of the microinverter. That improves power quality and minimizes the potential for disruptions in the grid [18], [19]. The damping filter is designed to ensure stability and optimal performance of the solar power system. It dampens oscillations and resonances within the system, preventing unwanted interactions between the system and the grid [20], [21]. LCL filters are commonly utilized in grid-connected inverters to reduce high-frequency harmonics and increase power quality. One of the primary advantages of LCL filters is their superior harmonic attenuation capability. They are more effective at reducing the high-frequency components than simpler LC or L filters [22], primarily due to their additional inductive to capacitive stages. The results in cleaner sinusoidal output are crucial for grid compliance and reduce electromagnetic interference (EMI) [23].

Another significant advantage of LCL filters is their ability to provide better filtering performance within a compact size and lower weight. The design of LCL filters allows for a higher attenuation of switching harmonics without necessitating excessively large filter components [24], [25]. This compactness is particularly valuable in applications with critical space and weight constraints, such as solar inverters. Designing and tuning LCL filters can be more challenging. Despite their advantages, LCL filters have primary disadvantages, such as complexity and the associated control challenges. The inclusion of additional reactive components complicates the filter design and system modelling. This complexity can lead to stability issues, necessitating sophisticated control algorithms to ensure the system remains stable under various operating conditions. Implementing these control strategies can be demanding regarding hardware and software resources [26], [27]. Another disadvantage is the potential for resonance issues. LCL filters are prone to resonance at certain frequencies, which can amplify undesirable harmonics instead of attenuating them. Additional passive or active damping methods are often required to mitigate resonance problems [28], [29]. These damping solutions may raise the overall cost and the system's complexity. Somewhat offsetting the benefits provided by the enhanced filtering performance of the LCL filter. Passive damping filters offer several advantages compared to LCL filters and H-bridge topologies, particularly in simplicity and reliability. One of the primary benefits of passive damping is its straightforward implementation because it relies on passive components, including resistors, capacitors, and inductors. Unlike active damping methods [30], [31], which require complex control algorithms and additional sensors, passive damping solutions are easier to design, implement, and maintain. This simplicity translates to increased system robustness and lower chances of failure due to fewer active components [32].

Passive damping filters also effectively mitigate resonance issues commonly associated with LCL filters. By carefully designing the passive elements, it is possible to attenuate resonance frequencies and increase the system stability without the need for advanced control strategies. Compared with H-bridge filters, the passive damping approach is often more cost-effective and reliable, especially in applications that reduce harmonic distortions and improve power quality, which is critical. Furthermore, passive damping does not suffer from the switching losses inherent in active solutions, ensuring higher efficiency of the overall power conversion system.

Total harmonic distortion (THD) is a critical parameter when evaluating the effectiveness of LCL filters in power electronic systems, particularly in grid-tied inverters [33]. LCL filters are highly effective in reducing harmonic distortion due to their ability to suppress high-frequency switching harmonics [34]. The component structure enables the LCL filter to provide steep roll-off characteristics, significantly minimizing THD and ensuring cleaner sinusoidal output. This reduction in harmonics is essential for complying with grid connection standards, thereby improving power quality [35]. However, an LCL filter can introduce resonance issues and, if not properly damped, can lead to spikes in harmonic distortion at certain frequencies. To address this, designers often incorporate passive or active damping techniques to stabilize the filter and ensure low THD levels across various operating conditions [36]. Although effective, these solutions add complexity to the system design, so harmonic attenuation, stability, and overall system efficiency must be balanced [37], [38]. Passive damping filters are important for regulating THD within power systems, offering a more straightforward approach than LCL filters [39]. By using passive filter components, the passive damping filters effectively reduce resonances that can cause harmonic distortions [40]. The main advantage of passive damping is its ability to mitigate these resonances without requiring active control algorithms, thus simplifying the system design. This passive approach helps maintain low THD levels in the output, ensuring the power quality is within acceptable limits for most applications [41]. Although passive damping filters may not offer the same level of harmonic attenuation as meticulously designed LCL filters, they balance performance and simplicity well. The resistive components in passive damping directly dissipate Energy that could otherwise contribute to harmonic distortion, thus providing a cleaner output. This method is particularly beneficial in applications where ease of implementation, reliability, and minimal maintenance are priorities. Passive damping filters can effectively maintain low THD in various power conversion systems, as well as efficiency, stability, and grid compatibility [42]. This paper is structured as follows: Section 2 describes the two-stage PV-microinverter and damping filter theory and explains the mathematical details of the (R//LC) filter and its harmonics-mitigating characteristics. Section 3, results and discussion, presents simulations results of the proposed system, bode diagram, and key parameters of the grid-connected PV-microinverter are provided. MATLAB simulations also compare system performance with the LCL filter, H-B damping filter, and damping filter. Results encompassing grid current are discussed under steady state and dynamic operation conditions. The conclusion shows the significance of the damping filter. This approach holds promise for efficient grid integration in PV systems by improving power quality and reducing harmonic distortions, contributing to sustainable energy solutions.

2. TWO-STAGE PV-MICROINVERTER

The block diagram in Figure 1 illustrates a PV panel connected to a boost converter, which raises the voltage from the PV panel to a suitable level for an H-bridge inverter. This inverter converts the DC into AC Current suitable for the grid, ensuring the output is a proper sinusoidal waveform [43]. The LCL output filter is used to reduce the harmonics generated by the inverter through pulse-width modulation (PWM) techniques [44], [45]. Additionally, the overall system integrates maximum power point tracking (MPPT) and phase-locked loop (PLL) algorithms to ensure efficient power delivery to the grid with a unity power factor. The two-stage PV microinverter with Q-boost converter and LCL output filters is a more advanced configuration in high-performance PV systems. In this microinverter methodology, the PV panel is integrated with a boost converter, which is subsequently connected to an H-bridge inverter that incorporates an LCL output filter.

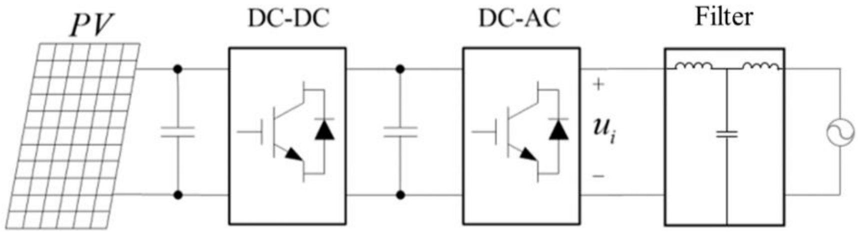

Figure 1. Block diagram of two-stage grid-tied PV-microinverter

Figure 2 depicts a circuit diagram of a two-stage grid-connected PV-microinverter, illustrating a system for efficient energy conversion in PV applications. This PV-microinverter system primarily comprises a PV array that captures solar energy. The generated voltage is initially stored in a capacitor, which acts as a buffer to stabilize the PV voltage. Following this storage phase, the capacitor is connected to a quadratic boost converter. This converter is essential for elevating the DC voltage to a higher level. The boosted DC voltage is then further stored in a DC-link capacitor, which maintains a constant voltage level at the input of the H-bridge inverter. The H-bridge inverter converts the stabilized DC voltage into AC voltage. LCL output filter is employed to ensure that the output current is smooth. This filter effectively reduces harmonic distortions, providing clean sine wave output compatible with grid requirements. The quadratic boost converter uses the square of the input voltage to increase the output voltage, offering greater efficiency than standard boost converters. Figure 3 depicts a two-stage grid-connected PV microinverter with a Q-boost converter and an LCL output filter.

2.1. Control scheme of two-stage PV-microinverter

The control strategy of a two-stage PV microinverter with an LCL filter consists of the current and voltage from P-V panel data, carried out by an appropriate maximum power point tracking (MPPT) algorithm. The DC bus voltage control algorithm gives a reference for the current injection into the grid, which is then synchronized with the grid and related to the phase-locked loop (PLL) algorithm. A proportional-resonant (PR) controller can closely monitor the current since its gains are infinite at some frequency [46]. The control algorithm is modified to realize passive damped with the help of sampling the current from the LCL filter capacitor, thus reducing the resonant peak of LCL filters [47]. It is also essential to consider the feedforward of grid voltage. A detailed description of phase-locked loop (PLL) algorithms for single-phase inverters is available elsewhere [48], [49]. The control scheme diagram of the PV-microinverter is shown in Figure 4.

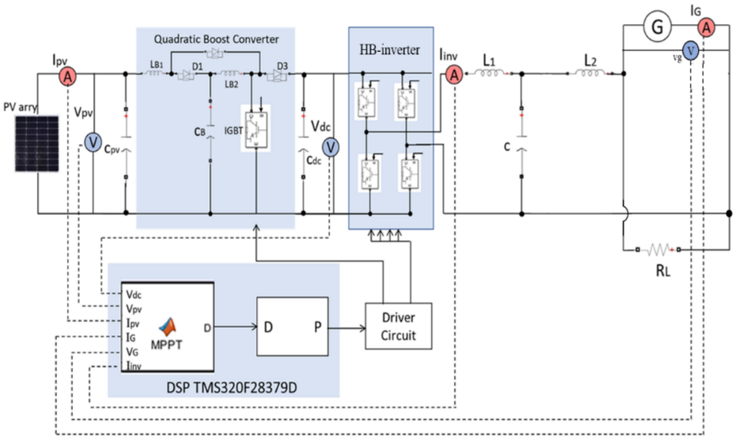

Figure 2. Circuit diagram of two-stage grid-connected PV-microinverter

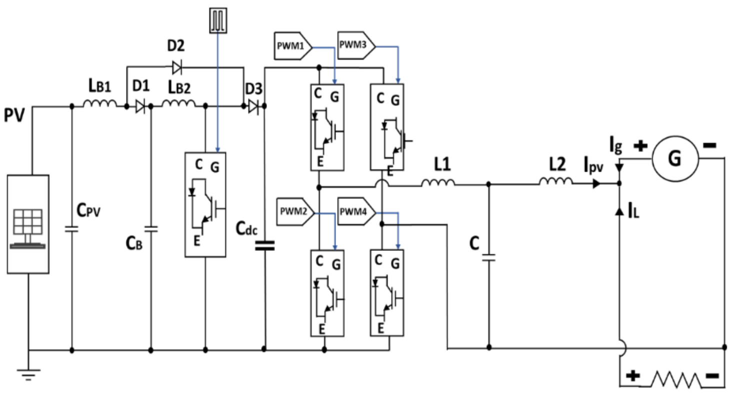

Figure 3. Circuit of two-stage grid-connected PV-microinverter

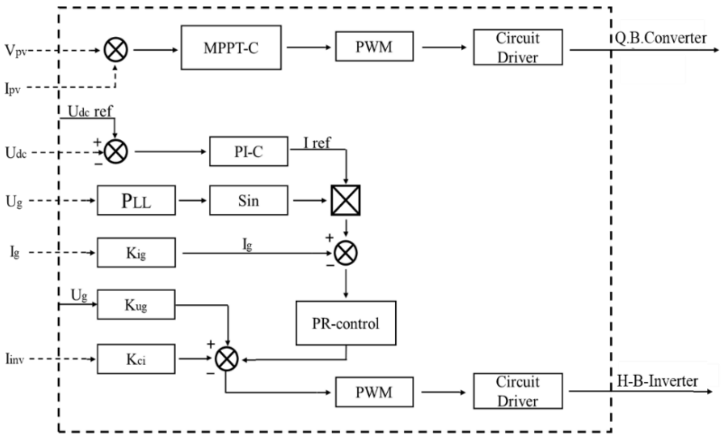

Figure 4. Control scheme of PV-microinverter with LCL

When dealing with sinusoidal references in grid-connected PV-microinverter, the PI controller may struggle to track them perfectly. The PR controller is often preferred for better tracking performance [50]. The grid-connected PV microinverter's proportional-resonant (PR) controller regulates the power flow from PV panels to the grid by introducing high gain at the resonant frequency. It typically consists of two parts. The first part is the proportional controller, which helps adjust the power output based on the error signal representing the difference between the desired output and the actual output.

It provides a proportional response to this error and adjusts the power output accordingly. The second part is the resonant controller, which is designed to handle certain frequency components in the system, allowing for better filtering and control of disturbances or harmonics that may occur in the system. This approach contributes to maintaining stability and improving the system's overall performance. Alongside the PR controller, it effectively optimizes the power transfer from the PV panels to the grid. Ensuring efficient operation and grid integration while maintaining system stability.

The PR controller can effectively track the current. Incorporating a passive damping filter through sampling the LCL filter capacitor current also helps to smooth out any resonance peaks that may occur in the system. A PR controller is preferred over a PI controller in grid-connected PV microinverters because it can handle dynamic changes, filter out harmonics, provide robust control in uncertain conditions, and ensure compliance with grid codes. Its dual-action nature offers improved performance and stability compared with the PI controller alone [51]. One of the major advantages of the PR controller is that it is a good way of adjusting output current according to the grid voltage setting, which mostly reduces harmonic distortion on the injected grid side. We do this by injecting resonant control action at the fundamental frequency of the grid, which enables our controller to effectively respond to both normal variations and disturbances in grid voltage.

2.2. LCL and (H-B) hybrid filter

LCL filters are important components in grid-connected PV microinverters, which are crucial in reducing harmonic distortion and improving overall system efficiency. This filter configuration typically consists of an inductor, a capacitor, and another inductor arranged in series. The LCL filter helps to mitigate high-frequency resonances and dampen harmonic currents, ensuring that the inverter operates smoothly and within grid compliance requirements. In the LCL H-leg's bridge, this configuration is a variation of the standard LCL filter design commonly used in microinverter systems. By utilizing an H-leg bridge topology, as shown in Figure 5, this filter offers improved attenuation of common-mode noise and better control of switching frequencies. The added H-leg structure enhances the overall performance of the LCL filter, making it suitable for demanding grid-connected applications where reliability and efficiency are paramount. The LCL H-leg's bridge configuration is a variation of the traditional LCL filter design, offering enhanced filtering performance for grid-connected PV microinverters. This setup incorporates an H-leg bridge topology, where additional components are added to the standard LCL filter to improve its filtering capabilities further. By introducing this bridge structure, the filter achieves better common-mode noise attenuation and provides more precise control over switching frequencies, which is essential for maintaining system efficiency and reliability [52]**.** The H-leg's bridge design enhances the filter's ability to reduce electromagnetic interference and suppress voltage harmonics, ensuring smoother power delivery to the grid. The improved filtering characteristics of the LCL H-legs make them well-suited for applications requiring stringent noise reduction and harmonic mitigation. By optimizing the filter topology with the H-leg's bridge, microinverter systems can operate more efficiently, meeting performance standards and grid requirements effectively. The LCL H-leg's bridge filter configuration offers advanced filtering capabilities, enhanced noise attenuation, and improved control over harmonic content, making it a valuable component in grid-connected PV microinverter systems.

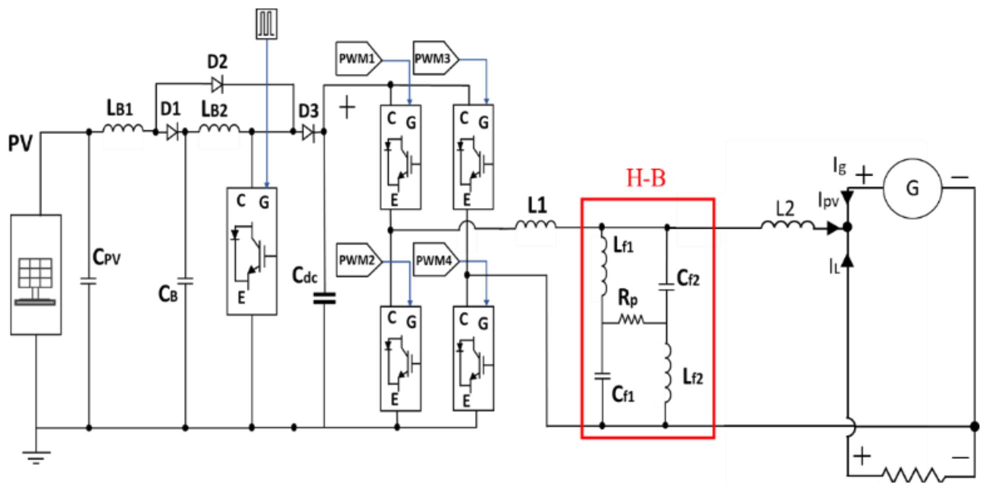

Figure 5. PV-microinverter with (LCL & H-B) hybrid filter

2.3. (LCL and PD) hybrid filter

The H-bridge inverter with LCL filter and passive damping filter converts the DC voltage from the quadratic boost converter into AC voltage, which is then connected to the grid or load. The H-bridge inverter consists of four switches (two in the upper arm and two in the lower arm) and uses high-frequency PWM to control the switching of the power devices and regulate the output voltage shown in Figure 6.

The LCL filter and damping filter together provide better filtering performance than using only one of them. LCL filter provides a high reduction of high-order harmonics, resulting in a cleaner and smoother output waveform. In contrast, the damping filter provides an effective reduction of high-order harmonics. Its low component count makes it an attractive choice for applications involving cost, weight, or space constraints. The combination of the quadratic boost converter and H-bridge inverter with LCL filter and damping filter (R//LC) provides a high-efficiency and high-performance PV system with better filtering performance, making it suitable for applications that require high-quality output waveforms.

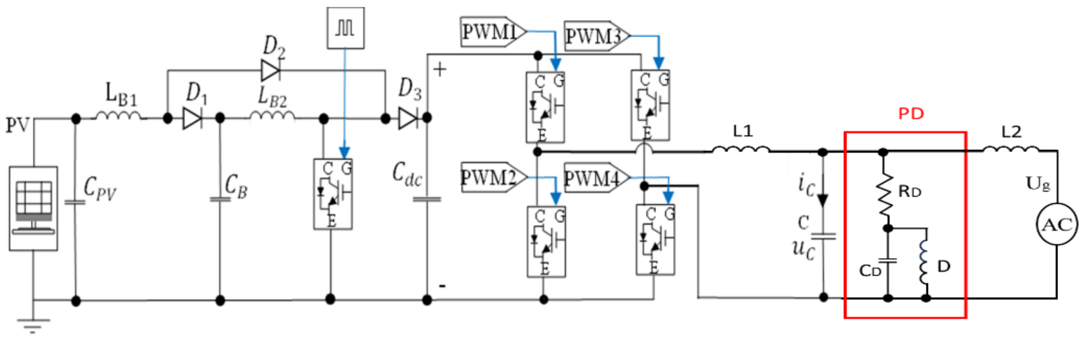

Figure 6. PV-microinverter with (LCL & PD) hybrid filter

LCL output filter topology is used in PV microinverters to reduce the THD of the output current waveform. The LCL filter tends to resonate at a certain frequency, which could cause effects within the subsystem. Degrades the filtering performance. LCL and (R//LC) passive damping filters are used in PV microinverters to enhance power quality by minimizing the grid current THD. LCL functions as a low-pass filter. Compared with the (R//LC) passive damping filter, improved power quality is achieved using an LCL filter, whose harmonic frequency reduction is better. On the other hand, using LCL filters is more costly in general, and district losses will potentially increase due to adding extra inductors.

The only simple design of these two Is the passive damping (R//LC) filter. It produces fewer harmonic frequencies in this type of filter as compared to the LCL filter, it is less costly, and power losses are low; addition, damping filters are usually easier to implement and calibrate, so they tend to be the favorite selection for PV small-scale microinverters. The performance of LCL filters is ideal for grid-interconnected applications with more stringent harmonic filtering requirements at large-scale PV systems; on the other hand, damping filters might be enough for smaller-sized installs, and cost-effectiveness (and simplicity) are primary considerations. The choice between LCL and damping filters is subject to various requirements of the PV-microinverter, the size of the system, grid interconnection standards and the economy of the PV-microinverter. The LCL and passive damping filters can reduce THD in the grid current. Adding an LC filter in parallel with the R in the (R//LC) damping filter and then cascading it with an LCL filter further improves the filtering performance by attenuating high-frequency harmonics. The LCL filter offers excellent attenuation of low-frequency harmonics. However, its ability to attenuate high-frequency harmonics is limited; incorporating an LC filter in parallel with the resistor in the damping filter can effectively attenuate high-order harmonics. The combination of filters results in a wider attenuation range, allowing for efficient suppression of high-order harmonics and subsequent reduction in grid current THD.

Add an (R//LC) damping filter parallel to the LCL filter to resolve this limitation. The damping resistor helps dissipate Energy accumulated in the resonant circuit of the LCL filter, while the combination of the inductor and capacitor creates a low-impedance path for high-frequency noise, integrating damping filter with the LCL filter enhances overall performance by reducing resonance peaks and minimizing high-frequency noise, this improvement also contributes to increased system stability by lowering the Q-factor of the resonant circuit, the mathematical analysis of the hybrid LCL and (R//LC) damping filter can be complex, and the design of the filter parameters requires careful consideration of the system requirements and limitations. However, by properly selecting the values of the damping resistor, inductor, and capacitor, a significant reduction in THD and improvement in the overall performance of the PV microinverter are possible.

Simultaneously, adding a damping (R//LC) filter parallel to LCL can significantly suppress the grid current resonance peaks and effectively reduce high-frequency disturbance, thus greatly improving the filtering property and declining low THD of grid current. In addition, it will improve system stability and reduce the Q-factor resonant circuit.

2.4. Mathematical modelling of (LCL-PD) hybrid filter

An LCL filter is frequently utilized in grid-connected PV microinverters to decrease high-frequency harmonics and guarantee that the inverter's output complies with grid requirements. The LCL filter is a component of the inverter's power electronics, which is essential in improving the energy quality supplied to the grid.

The basic design of the LCL filter can be illustrated as follows: V_{in} is the (PV) DC-voltage input, the inverter represents the PV-microinverter, L_1 and L_2 are inductors, C is the capacitor, and R_{Load} is the grid or load resistance. The LCL filter mathematical equation can be obtained by considering the impedance of the filter circuit.

The LCL filter total impedance can be defined as:

$$Z(s) = R_{Load} + sL_2 + sC_1 + sL_1 \tag{1}$$

(s) is the complex frequency variable, expressed as (s = j ω), where (j) represents the imaginary unit and (ω) denotes the angular frequency. (R_{Load}) is the load resistance, while (L_1) and (L_2) represent filter inductances, and C indicates the filter capacitance. The LCL filter transfer function can be obtained by rearranging the equation in the Laplace domain:

$$H(s) = \frac{V_{out(s)}}{V_{in(s)}} = \frac{1}{Z_{(s)}} \tag{2}$$

Description of the mathematical equation and transfer function step-by-step guide of LCL filter in two-stage PV-microinverter involves applying Kirchhoff's voltage law to the loop consisting of (L_1), (C) and (R_{Load}):

$$V_{in} = V_{L1} - V_C - V_{Rload} = 0 \tag{3}$$

The voltage across each element can be expressed as:
Voltage across L_1:

$$V_{L1} = L_1 \frac{di}{dt} \tag{4}$$

The voltage across C:

$$V_C = \frac{1}{C} \int idt \tag{5}$$

Voltage across R_{Load}:

$$V_{RLoad} = R_{Load} \cdot i. \tag{6}$$

The expressions for voltage across (L_1), (C) and (R_{Load}) are combined to express the current (i) in terms of (V_{in}) And its derivatives:

$$V_{in} = L_1 \frac{di}{dt} + \frac{1}{C} \int idt + R_{Load} \cdot i \tag{7}$$

The Laplace transform is a technique that transforms differential equations from the time domain into algebraic equations in the s-domain, commonly known as the complex frequency domain. The transformation of the $f(t)$ function is represented as $F(s)$. By applying the Laplace transform to both sides of the equation, we derive the following expression:

$$\iota\{V_{in}\} = L_1 sI(s) + \frac{1}{Cs} I(s) + R_{Load}\, I(s) \tag{8}$$

To express for the current through the circuit in the Laplace domain. This method enables us to examine the circuit's behavior in the s-domain, making it easier to solve for the current $I(s)$ when given. V_{in}(s). Once $I(s)$ is found, the inverse Laplace transform can calculate $i(t)$ in the time domain.
It solves the current $I(s)$ in terms of V_{in}(s):

$$I(s) = \frac{V_{in}(s)}{L_1 s + \frac{1}{Cs} + R_{Load}} \tag{9}$$

To summarize, it derived the output voltage. Using the Laplace transform, $V_{out}(s)$ across the load and resistor (R_{Load}) in the RLC circuit. The final expression provides a clear understanding of how the circuit components affect the output in the s-domain. The output voltage $V_{out}(s)$ is the voltage across the resistor load, which is simply ($R_{Load} I(s)$):

$$V_{out}(s) = R_{Load} \cdot \frac{V_{in}(s)}{L_1 s + \frac{1}{Cs} + R_{Load}} \tag{10}$$

The transfer function H(s) characterizes the system as the relationship between the Laplace transform of the output voltage, $V_{out}(s)$, and the Laplace transform of the input voltage, $V_{in}(s)$. This definition enables the transfer function to be represented as H(s).

The transfer function is an important tool for understanding how the system responds to various frequencies in the input signal, offering valuable insights into its behavior and stability; it encapsulates the system's dynamics in the s-domain and serves as an essential tool in control systems. The transfer function H(s) represents the ratio of the output voltage to the input voltage, indicating their relationship.

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{R_{Load}}{L_1 s + \frac{1}{Cs} + R_{Load}} \tag{11}$$

The transfer function H(s) captures the fundamental characteristics of the RLC circuit, illustrating the relationship between the output voltage. $V_{out}(s)$ and the input voltage $V_{in}(s)$As governed by the circuit components, the LCL filter transfer function is given by:

$$H_{LCL}(s) = \frac{R_{Load}}{L_1 s + \frac{1}{Cs} + R_{Load}} \tag{12}$$

That shows how the transfer function of an LCL filter in a two-stage grid-connected PV microinverter can help design and tune the output filter for desired performance and stability. The hybrid filter transfer function is described in detail, considering the LCL and passive damping filter (PD).

2.5. Reduction of grid current THD in PV-microinverter

The hybrid LCL filter and passive damping PD filter are designed to reduce grid current THD produced by the PV microinverter. Reducing THD is essential to complying with IEEE standards and regulations, which typically restrict the levels of harmonic distortion in the grid.

The hybrid filter can contribute to reducing grid current THD in the following ways:

a. Harmonic filtering with LCL filter: The LCL filter minimizes high-frequency harmonics produced by the inverter's switching operation. It provides a low-impedance path for high-frequency components, effectively preventing these harmonics from being injected into the grid.
b. Damping of resonances: The damping elements in the PD filter help dampen resonances within the system. Resonances can occur at certain frequencies resulting from the interaction between the inverter's impedance and the grid. Damping these resonances reduces the amplitude of specific harmonic components, contributing to THD reduction.
c. Improved control and stability: The hybrid filter design, when properly tuned, can improve the inverter's control and stability. This improvement can help mitigate the risk of grid current distortion, especially during transient conditions or grid variations.

The combination of LCL and PD elements allows for selective filtering of specific harmonics; the LCL filter may be more effective at certain frequencies, while the PD filter addresses others; this flexibility in filtering characteristics helps achieve a more comprehensive reduction in THD. The parameters of the LCL and PD filters must be carefully selected and tuned to achieve optimal performance, and this involves considering the resonance frequencies, damping ratios, and other characteristics to ensure effective harmonic mitigation without compromising system stability. The design and implementation of the hybrid filter should follow relevant IEEE standards and guidelines, which ensure that the grid-connected PV system meets the required limits for harmonic distortion.

Reducing grid current THD using a hybrid filter involves designing and tuning the filter to minimize the amplitude of the grid current waveform harmonic components. Although providing a single formula for THD reduction is challenging due to the complexity of the system and the interplay of various parameters, we can express the general concept mathematically.

- Let $I_{grid}(t)$ be the grid current.
- $I_{grid_{fund}}$(t) be a fundamental frequency component.

THD is usually defined as the ratio of the harmonic distortion's root mean square (RMS) value to the fundamental frequency component's RMS value.

$$THD = \frac{\sqrt{I_{grid}^2 - I_{grid\_fund}^2}}{I_{grid\_fund}} \quad (13)$$

A well-designed hybrid filter significantly reduces harmonic distortions in the inverter current, by filtering out specific unwanted frequencies, the grid current becomes cleaner and closer to sinusoidal waveform, which is ideal for grid stability and power quality. The hybrid filter also affects the dynamic operation response of the grid current; if rapid changes occur in the inverter current, the filter modulates these changes depending on its design parameters, such as cutoff frequencies and the steepness of the roll-off. We consider the impact of the hybrid filter transfer function. $H_{hybrid}(s)$ on the grid current:

$$I_{grid}(t) = H_{hybrid}(j\omega) \cdot I_{inverter}(t) \quad (14)$$

In the frequency domain, the hybrid filter's effect on the grid current revolves around its ability to amplify or attenuate the fundamental frequency component within the inverter's grid current, by focusing on the fundamental frequency component, the filter's magnitude response determines the amplitude scaling and harmonic reduction at that specific frequency, this ensures clean signal at the desired frequency, improving power quality and overall system efficiency. Here, $I_{inverter}(t)$ is the output current of the inverter. To simplify the discussion, we focus on the frequency domain (ω):

$$I_{grid\_fund}(\omega) = \left|H_{hybrid}(j\omega)\right| \cdot I_{inverter\_fund}(\omega) \quad (15)$$

Here, $I_{inverter\_fund}(\omega)$ represents the fundamental frequency component associated with the grid current; it assumes that the hybrid filter effectively attenuates harmonic components $H_{hybrid}(j\omega) = 0$ for ($\omega \neq \omega_{fund}$), we can express the THD reduction:

$$THD_{filtered} = \frac{\sqrt{I_{grid\_filtered}^2 - I_{grid\_fund\_filtered}^2}}{I_{grid\_fund\_filtered}} < THD_{inverter} \quad (16)$$

Here, $THD_{filtered}$ is the grid current (THD) after passing through the hybrid filter, $THD_{inverter}$ is the inverter output current (THD), $I_{grid\_filtered}$ is the grid current after passing through the hybrid filter, and $I_{grid\_fund\_filtered}$ is the fundamental frequency component of the grid current after passing through the hybrid filter.

The specific mathematical form of $H_{hybrid}(j\omega)$ and the reduction in THD depends on the detailed transfer function of the hybrid filter. A hybrid filter's advantage over an LCL filter for reducing grid current THD lies in its ability to combine the benefits of LCL and parallel filter (PD) elements. The hybrid filter aims to address the limitations of the LCL filter, such as resonance issues and higher losses at certain frequencies. The grid benefits from improved power quality with fewer harmonics and noise, leading to better performance PV-microinverters connected to the grid. The use of hybrid filters helps meet regulatory standards for harmonic emissions and power quality, ensuring that the inverter's contributions to the grid do not violate established limits.

As affected by the hybrid filter, the analysis of fundamental frequency components in the frequency domain highlights the importance of maintaining clean, stabilized fundamental frequency in the grid current. Furthermore, optimizing the transmission of the fundamental frequency and mitigating harmonics, the hybrid filter (LCL and PD) contributes significantly to power system stability, efficiency, and compliance with industry standards.

3. RESULTS AND DISCUSSION

3.1. Bode diagram of PV-microinverter

Figure 7 describes the bode diagram of a PV microinverter in both conditions, with and without a damping filter. The bode diagram is a graph displaying the system's frequency response, or how the magnitude and phase shift of any given input changes at different frequencies. It also compares the bode diagrams of PV microinverters with and without a damping filter to illustrate how it affects frequency response.

PV-microinverter without a damping filter, the PV-microinverter is connected directly to the grid via an LCL filter, which primarily reduces harmonic distortion in the grid current. However, without a damping filter, the LCL filter may experience resonance at certain frequencies due to the inductors' and capacitors' interaction. This resonance occurs because the inductive and capacitive reactance can become equal and opposite, leading to increased oscillations at specific frequencies. These oscillations can result in the output, impacting the overall system's stability and performance. From the bode diagram of the unfiltered system, the resonant peak exists at an effective frequency due to LCL filter resonance; the phase response has changed a lot at the resonant frequency, and this resonance can lead to stability issues, such as voltage overshoots and increased harmonic distortion or system instability.

PV-microinverter with damping filter, using damping filter in the system to low-pass filter can help reduce resonance and increase stability; this filter increases the impedance added to the LCL filer, hence reducing the additional magnitude of a resonance peak in frequency response, the presence of these controlled resonances and the resultant oscillations are dampened by the damping filter, thereby not only stabilizing but also reducing THD in grid current, this is achieved through the smoothing of current and voltage ramps, thereby producing cleaner power output that can more consistently meet grid code requirements from an electrical point of view like in complying with grid connection standards.

Figure 7 provides a bode plot for the dampened resonant filter scenario and shows that this reduces the magnitude of the resonance frequency. The phase response is also improved, with a smaller shift in the phase at the resonant frequency. This behavior leads to the unstable performance of a system that is stabilized by conventional design criteria.

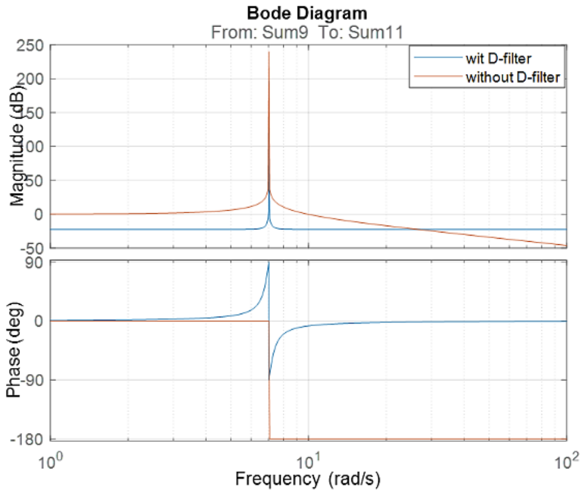

Figure 7. Bode diagram of PV-microinverter without and with damping filter

3.2. System parameter OF PV-microinverter

Table 1 shows the PV-microinverter system parameters, including a fundamental frequency of 50 Hz for synchronization and a switching frequency of 10 kHz to ensure efficient power conversion. The PV panels provide a voltage of 31.7 V DC and a current of 8.7 A DC, which is boosted to 400 V DC for effective conversion. The grid operates at a phase voltage of 220 V AC and a current of 1.5 A AC to facilitate seamless interaction. Component specifications are critical for maintaining stability, reducing grid current (THD), and ensuring compliance with grid standards. These specifications include PV capacitance of 500 μF, boost inductors of 40 μH and 120 μH, and boost capacitance of 10 μF. Additionally, DC-link capacitance of 1.5 mF, LCL filter elements consisting of a 1.2 mH inductor and 20 μF capacitor are specified. Each parameter is carefully selected to ensure the microinverter operates reliably, minimizes THD in the grid current, and adheres to grid standards.

Table 1. PV-microinverter system parameters

Symbol	Name	Value
f_1	Main frequency	50 Hz
f_s	Switching frequency	10 kHz
V_{PV}	Photovoltaic voltage	31.7 V-DC
I_{PV}	Photovoltaic current	8.7 A-DC
V_{Boost}	Boost voltage	400 V-DC
V_G	Grid phase voltage (RMS)	220 V-AC
I_G	Grid phase current (RMS)	18A-AC
C_{PV}	PV capacitance	500 μF
L_{B1}	Boost inductor 1	60 μH
L_{B2}	Boost inductor 2	120 μH
C_B	Boost capacitance	10 μF
C_{dc}	DC-Link capacitance	500 μF
L_1	LCL inductor	1.2 mH
L_2	LCL inductor	1.2 mH
C	LCL capacitor	20 μF

3.2.1. SIMULATION OF PV-MICROINVERTER AT STEADY STATE OPERATION

This study employed MATLAB Simulink as the simulation platform to develop and assess grid-tied PV-microinverter topology, and the simulation outcomes serve as valuable means to show the design's effectiveness and performance. MATLAB simulation results of the grid current THD using different filters, specifically the LCL filter, (H-B) filter, and (PD) passive damping filter, demonstrate the effectiveness of these filters in reducing grid current THD. Figure 8 provides a view of the grid voltage under steady-state operation.

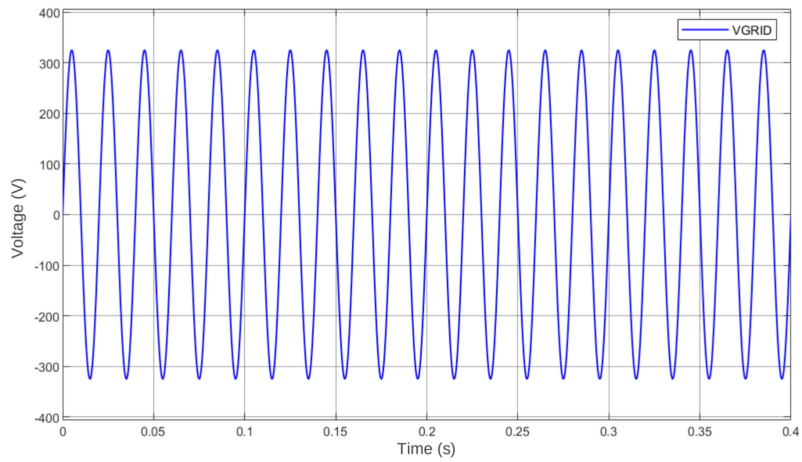

Figure 8. PV-microinverter grid voltage

The PD damping filter played an important role in attenuating harmonic distortions. This observation highlights the PD damping filter's effectiveness in reducing harmonic distortions, which leads to cleaner grid voltage. The figures provide a dual perspective on the grid voltage, demonstrating its stability in steady-state and dynamic response operation and its freedom from harmonics. During steady-state operation, the microinverter modifies the output voltage to meet the specifications of the grid, maintaining a stable and consistent power supply. In dynamic response situations, such as when nonlinear loads are present, the microinverter swiftly adjusts its output voltage to compensate for fluctuations and ensure a smooth transfer of Energy to the grid.

Figure 9 illustrates the grid current waveform of a PV microinverter operating without a damping filter. The measured grid current is 2 A, but the THD is notably high, reaching approximately 10%. This significant level of THD indicates severe distortion in the AC waveform of the grid current, which directly impacts the quality of power being injected back into the grid. Such high harmonic content not only degrades the sinusoidal purity of the current but also introduces inefficiencies and potential instability in the grid system. Harmonics can cause overheating of grid components, interference with other connected devices, and increased losses, ultimately reducing the overall reliability and performance of the power system.

Compared to other topologies, such as those incorporating active or passive damping filters, the performance of the PV microinverter without a damping filter is notably inferior. For instance, topologies utilizing LCL filters with active damping techniques have been shown to significantly reduce THD levels, often to below 5% or even lower, depending on the design and control strategy. These topologies effectively suppress harmonic components, resulting in a cleaner grid current waveform and improved power quality. Similarly, systems employing advanced control algorithms, such as proportional-resonant (PR) controllers, enhance harmonic mitigation and ensure smoother grid integration.

In contrast, the absence of a damping filter in the topology is shown in Figure 9 leads to higher THD, which is unacceptable for grid-connected applications were strict power quality standards, such as IEEE 519, must be met. The results emphasize the importance of incorporating effective filtering and control mechanisms in PV microinverter designs to minimize harmonic distortion and ensure compliance with grid codes. This comparison highlights the trade-offs between simpler, filterless topologies and more complex, filter-enhanced systems, with the latter offering superior power quality and grid stability performance. Future work could explore hybrid approaches that balance cost, complexity, and performance to achieve optimal results in PV microinverter applications.

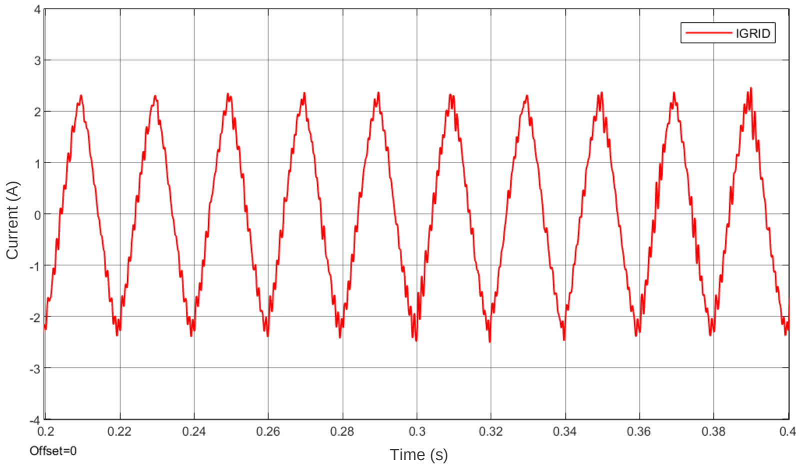

Figure 9. PV-microinverter grid current with LCL filter at SS

The distortion of the grid current is measured at approximately 10%, as shown in Figure 10. The high THD value reflects considerable harmonic distortion, which can adversely affect the power quality supplied to the grid. This level of distortion may lead to several issues, such as inefficiencies in power delivery, the potential for equipment overheating, and increased losses. Additionally, such distortion can cause non-compliance with grid standards, which are established to ensure that electrical systems operate reliably and efficiently without causing interference or instability in the grid.

Figure 10 and Figure 11 highlight the challenges associated with high THD in grid-connected PV microinverter systems. Without effective filtering, the grid current exhibits a THD of around 10%, as shown in Figure 10, while Figure 11 demonstrates the corresponding impact on grid power quality. Such high levels of distortion can lead to inefficiencies, increased losses, and potential instability in the grid, emphasizing the need for effective harmonic mitigation strategies. PD (passive damping) filter has been implemented to suppress harmonic components and improve system performance.

The PD passive damping filter utilizes passive components, such as resistors, capacitors, and inductors, to attenuate harmonic frequencies and dampen resonance effects in the system. This approach is particularly effective in LCL filter-based systems, where resonance can exacerbate harmonic distortion. By introducing damping resistors, the PD filter reduces resonance peaks and lowers THD levels, resulting in cleaner grid current waveform and improved power quality. The PD passive damping filter offers a simpler and more cost-effective solution than active damping methods, which rely on complex control algorithms and additional hardware

Implementing the PD passive damping filter reduces THD, often below 5%, ensuring compliance with power quality standards such as IEEE 519. While active damping techniques may provide superior performance, they increase system complexity and cost. In contrast, the PD passive damping filter balances performance, simplicity, and reliability, making it a practical choice for many grid-connected applications.

Future research could explore hybrid approaches combining passive damping with advanced control strategies to enhance harmonic suppression and system efficiency. The PD passive damping filter is a key solution for improving power quality and ensuring the stable operation of renewable energy systems integrated into the grid.

Figure 12 shows the grid current of the PV-microinverter using an (H-B) damping filter. The grid current equals 4 A, and the THD is lower than the LCL filter without damping, indicating improved grid current quality. However, THD still exceeds the interconnection requirement of less than 5%, as specified by standards like IEEE 519. This limitation highlights the need for further refinement in the filtering approach. Additional damping filters have been developed and implemented in parallel with the LCL filter. These hybrid configurations enhance harmonic suppression, reducing THD to acceptable levels and ensuring compliance with grid interconnection standards. By combining the strengths of multiple filtering techniques, the system achieves better power quality, minimizing harmonic distortion and its negative effects on grid stability and equipment performance. This advancement demonstrates the importance of innovative filtering solutions in improving the reliability and efficiency of grid-connected PV systems.

Figure 13 illustrates the THD achieved using the (H-B) damping filter in the PV-microinverter system. The THD is approximately 6%, as shown in the Figure 13. While the H-B damping filter significantly reduces harmonic distortion compared to systems without damping, it still falls short of meeting the grid interconnection requirements, which typically mandate THD of less than 5%. The H-B damping filter effectively suppresses many harmonic components, improving grid current quality and more sinusoidal waveform. However, the remaining distortion indicates that further enhancements are necessary to comply with grid standards and ensure optimal power quality fully. This limitation underscores the need for additional filtering techniques or hybrid approaches, such as combining the H-B filter with other damping methods, to achieve the desired THD levels and enhance the overall performance of grid-connected PV systems.

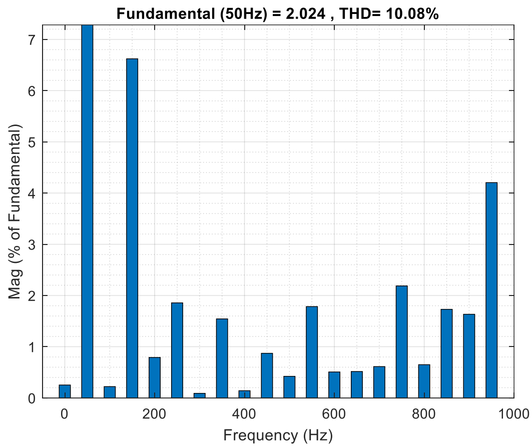

Figure 10. PV-microinverter grid current THD with LCL filter at SS

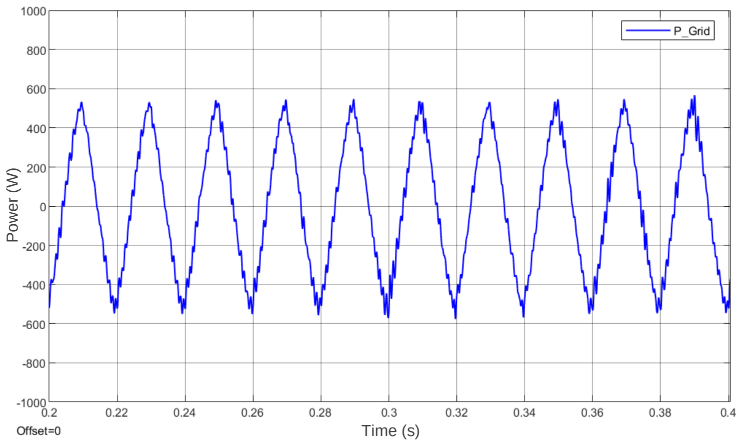

Figure 11. PV-microinverter grid power with LCL filter at SS

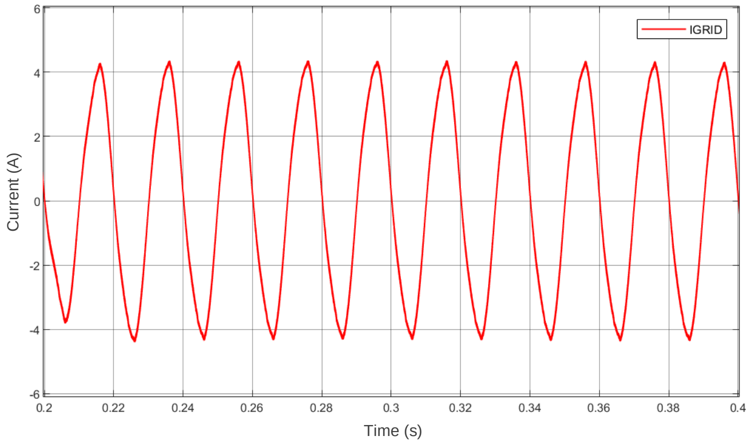

Figure 12. PV-microinverter grid current with H-B filter at SS

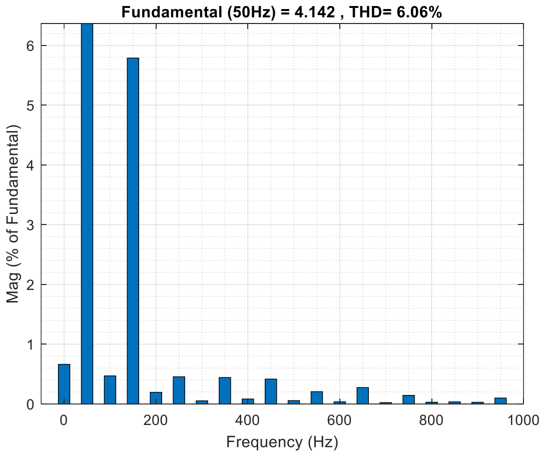

Figure 13. PV-microinverter grid current THD with H-B filter at SS

Figure 14 demonstrates the grid power waveform when the (H-B) damping filter is incorporated into the PV-microinverter system. Including the (H-B) filter results in a notable reduction in THD, as visually evident in the Figure. Compared to previous cases without the damping filter, where the THD was around 10%, the integration of the H-B filter reduces the THD to 6%. This significant improvement highlights the effectiveness of the H-B damping filter in mitigating harmonic distortions and enhancing the grid power quality. The reduction in THD underscores the capability of the H-B damping filter to suppress harmonic components, resulting in a cleaner and more sinusoidal grid power waveform. While this improvement is substantial, the THD level of 6% still does not fully meet the grid interconnection requirements, which typically demand less than 5% THD. Nevertheless, the results demonstrate the potential of the H-B damping filter as a valuable step toward achieving better power quality. Further refinements or hybrid filtering approaches may be necessary to comply with grid standards and ensure optimal performance in grid-connected PV systems.

Figure 15 illustrates the grid current of a PV microinverter system incorporating a PD (passive damping) filter. In this configuration, the grid current is about 4 A, and the THD is significantly reduced to around 3.75%. This low THD level demonstrates the effectiveness of the PD damping filter in mitigating harmonic distortion and improving the quality of the grid current. Importantly, the THD of 3.73% meets the grid interconnection requirements, which typically mandate less than 5% according to standards such as IEEE 519.

Compared to other topologies, the PD damping filter shows superior performance. For instance, in the case of an LCL filter without any damping, the THD was around 10%, indicating significant harmonic distortion and poor compliance with grid standards. Adding an H-B (bridge-based) damping filter to the LCL topology reduced the THD to approximately 6%, representing improvement but falling short of the required threshold. In contrast, the PD damping filter achieves a THD of just 3.73%, surpassing the performance of both the standalone LCL filter and the LCL filter combined with the H-B damping filter.

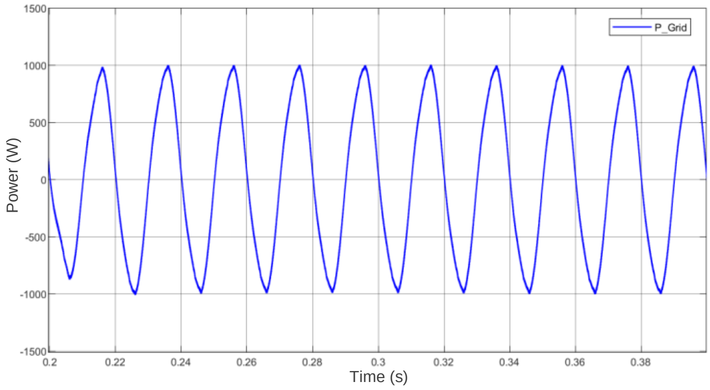

Figure 14. PV-microinverter grid power with H-B filter at SS

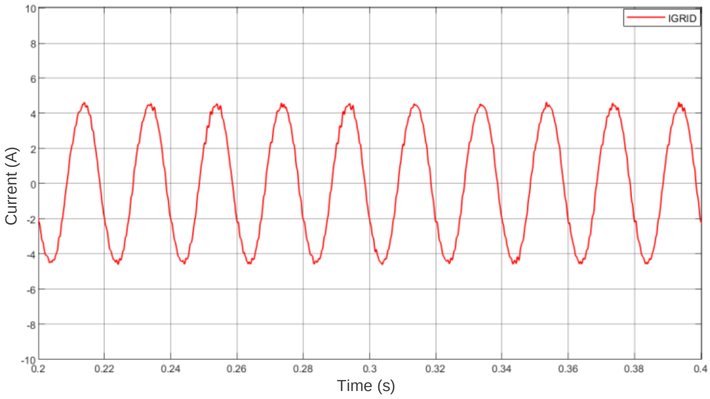

Figure 15. PV-microinverter grid current with PD filter at SS

The THD of the grid current, measured at 4 A, has been significantly reduced to 3.73% through the effective implementation of damping filters. These filters play a critical role in attenuating harmonic components that distort the waveform, resulting in a much cleaner and more sinusoidal current. The reduction in THD demonstrates the filter's ability to suppress harmonic distortion effectively, leading to a purer grid current waveform. This improvement is essential for ensuring compliance with grid interconnection standards, which mandate less than 5% THD. By meeting these requirements, the damping filter enhances the stability and reliability of power distribution systems, ensuring smoother integration of renewable energy sources like PV-microinverters into the grid. The results highlight the importance of advanced filtering techniques in achieving high power quality and maintaining the integrity of grid-connected systems. Figure 16 shows the PV-microinverter grid current THD with PD filter at SS.

The reduction in THD from 10% to just 3.73% represents a significant enhancement in power quality, effectively minimizing the adverse effects of harmonics, such as equipment overheating, increased energy losses, and interference with other connected devices. This improvement ensures compliance with regulatory standards for grid connectivity and optimizes the PV-microinverter system's performance and efficiency. By delivering cleaner, higher-quality power, the system enhances overall reliability and contributes to the longevity of grid-connected equipment. This advancement supports the sustainable integration of renewable energy sources into the grid, promoting a more stable and efficient power distribution network. The results underscore the importance of advanced filtering techniques in achieving superior power quality and fostering the reliable operation of renewable energy systems. Figure 17 illustrates the steady state of grid power when the PD damping filter is incorporated; this improvement is visually evident compared with previous instances.

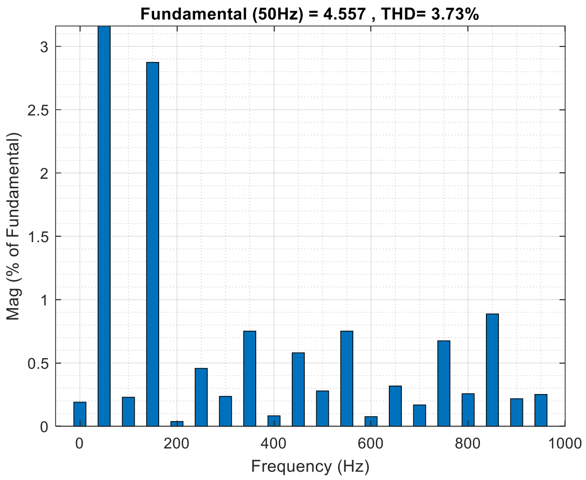

Figure 16. PV-microinverter grid current THD with PD filter at SS

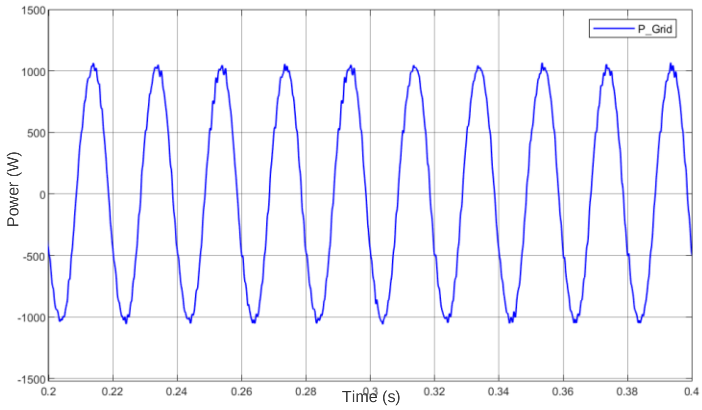

Figure 17. PV-microinverter grid power with PD filter at SS

3.2.2. Simulation of PV-microinverter at dynamic operation

Figure 18 illustrates the grid current of a PV-microinverter utilizing an LCL filter during dynamic response operations with nonlinear load transitioning from inductive (L) to capacitive (C); during operation with the inductive load, the grid current measures 2 A, while it increases to 2.5 A when shifting to the capacitive load. Despite this dynamic performance, the THD is notably high, recording approximately 10.33%. This elevated level of harmonic distortion indicates that the waveform of the grid current is significantly distorted, which can lead to potential power quality issues and may impact the performance of other connected devices.

Figure 19 illustrates the THD in a two-stage grid-connected system with an LCL output filter under nonlinear load conditions. The results indicate that the THD is relatively high, exceeding 10%, and the system's time response is also prolonged, taking 0.08 milliseconds to stabilize after transitioning from inductive to capacitive load. That highlights a significant challenge in the current filter topology, as the high THD and slow response time can compromise power quality and system stability. Optimizing the LCL filter design to minimize the THD and the system's time response is essential to address these issues. Improving the filter topology would enhance the system's ability to handle dynamic load changes efficiently, ensuring smoother transitions, reduced harmonic distortion, and better performance under nonlinear load conditions. Such optimization is critical for achieving reliable and stable operation in grid-connected photovoltaic systems.

Figure 20 displays the grid current of the PV microinverter with (H-B) damping filter at dynamic response operation under nonlinear load from inductance load L with 4.25 A to capacitive load C with 4.0 A. The THD is lower than the first method LCL without a damping filter, measuring around 6%. Although the (H-B) damping filter effectively reduces THD, it fails to satisfy grid requirements and improve power quality.

Implementing the (H-B) damping filter in conjunction with the LCL filter has demonstrated significant improvement in reducing the THD of the grid current, as shown in Figure 21. Specifically, the THD decreased from 10% to 6% during dynamic response operation, highlighting the hybrid filter's capability to mitigate harmonic distortions effectively. This improvement is particularly evident during the transition from inductive to capacitive load, where the system achieves stability within 0.02 seconds. The hybrid (LCL and H-B) filter reduces harmonic distortion and enhances the system's dynamic response, making it more robust under nonlinear load conditions.

However, despite these advancements, the system still falls short of meeting the IEEE standards for power quality. Additionally, the hybrid filter introduces higher power losses than the standalone LCL filter. While the hybrid topology represents a clear improvement over the conventional LCL filter, further optimization is necessary to address these limitations. The critical goal is to enhance the filter design to reduce power losses and achieve compliance with IEEE standards. Such refinement will ensure the system delivers higher efficiency, improved stability, and superior power quality, making it more suitable for grid-connected PV applications.

Figure 22 illustrates the PV microinverter grid current with a PD damping filter. The grid current at inductive nonlinear load equals 4.63 A, the capacitive load equals 5.08 A, and the (THD) is low, measuring just around 4%. Grid current (THD) is reduced to 4% at dynamic response operation under nonlinear, inductive, and capacitance loads. The PD The damping filter minimizes harmonic components in the grid current, producing a cleaner and more sinusoidal waveform. This improvement is reflected in the reduced THD value, demonstrating effective suppression of harmonic distortion. Thereby complying with grid standards and improving overall power quality.

The reduction in THD from 10% to 4% marks a significant advancement in the power quality of a PV microinverter system, as illustrated in Figure 23. The LCL filter combined with a passive damping (PD) filter significantly reduces THD compared to the hybrid LCL and H-B filter topology. The LCL-PD filter achieves a remarkable reduction in harmonic distortion and ensures a faster dynamic response, enabling the system to meet the rigorous IEEE standards for power quality. Furthermore, this filter topology is highly efficient, exceeding 95%, making it an ideal solution for two-stage grid-connected PV microinverter systems. By combining low THD, compliance with power quality standards, and high efficiency, the LCL-PD filter emerges as an optimized and reliable solution for integrating renewable energy systems into the grid. Its performance highlights its potential to enhance the stability, efficiency, and overall effectiveness of PV microinverter systems, paving the way for more sustainable and resilient energy solutions.

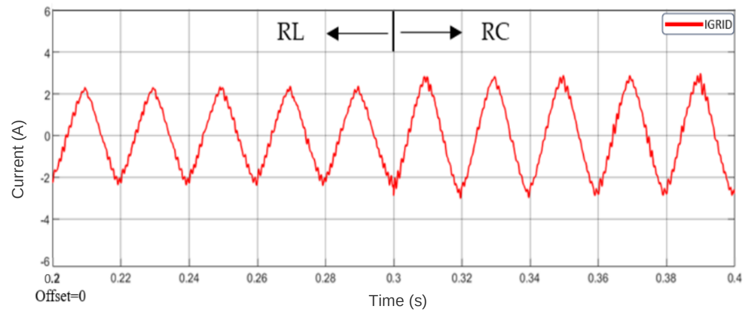

Figure 18. PV-microinverter grid current with LCL filter at DR

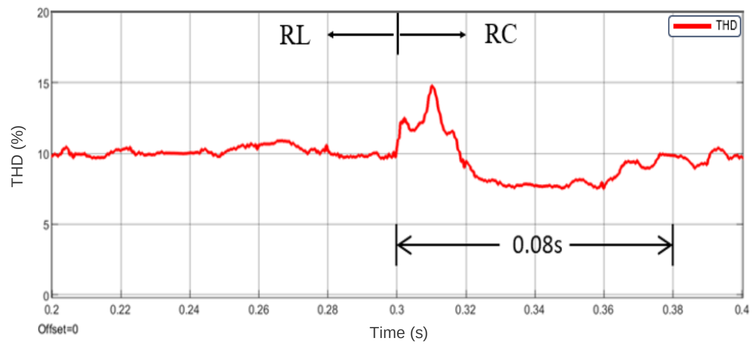

Figure 19. Grid current THD with LCL filter in nonlinear load at DR

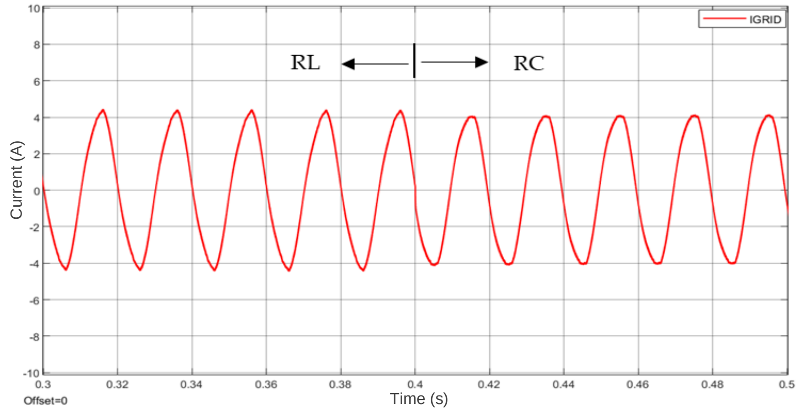

Figure 20. PV-microinverter grid current with (H-B) filter at DR

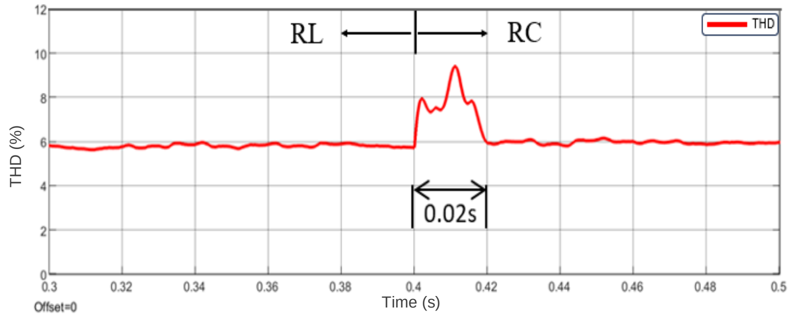

Figure 21. Grid current THD with H-B filter in nonlinear load at DR

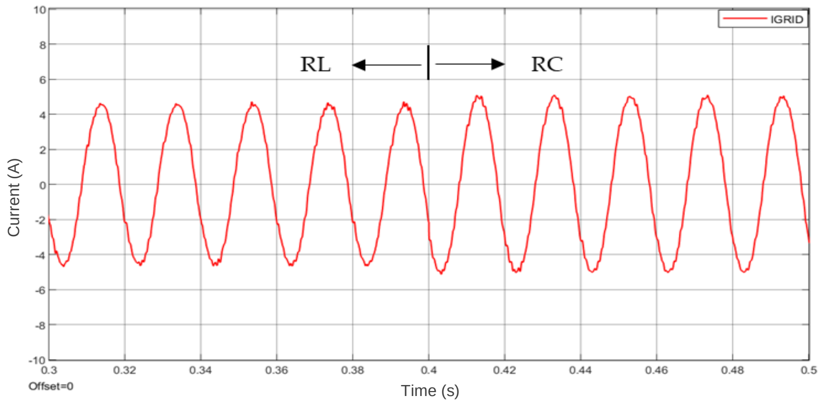

Figure 22. PV-microinverter grid current with PD filter at DR

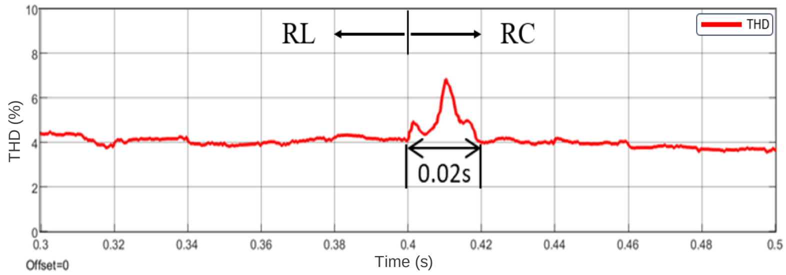

Figure 23. Grid current THD with PD filter in nonlinear load at DR

3.2.3. Efficiency of grid-connected PV-microinverter

The PV-microinverter efficiency with the (LCL and PD) hybrid filter depends on various factors, including the design and tuning of the hybrid filter, control strategies, and the specific characteristics of the PV system and grid. The hybrid filter introduces additional losses due to the passive components in both the LCL and PD sections. Minimizing these losses is crucial for overall system efficiency.

The efficiency of the control strategy employed to manage the hybrid filter's operation and coordination with the microinverter impacts system performance. Adaptive control algorithms can optimize filter parameters dynamically. The hybrid filter must be seamlessly integrated with the microinverter to ensure effective filtering without compromising the inverter's efficiency. Control coordination is essential for optimal power transfer. The hybrid filter's effectiveness in reducing grid current THD influences the system's overall efficiency. If it successfully mitigates harmonics, it can improve the power quality and reduce losses.

Table 2 presents the simulation results for (V_{out}), (I_{out}), (P_{out}), THD, and Efficiency. The values in the table demonstrate how each parameter varies under different filter configurations: just an LCL filter, with an H-bridge damping filter, and a passive damping filter. This analysis presents the performance and characteristics of the grid-connected PV microinverter system under these specific conditions.

The comparison demonstrates the effectiveness of the (R//LC) damping filter in reducing harmonic distortion in the grid current waveform. Simulation results underscore the importance of incorporating (R//LC) damping filters in H-bridge PV microinverters to mitigate issues related to harmonic distortion effectively. Specific THD values achieved in simulations may vary depending on the system configuration, filter design parameters, control strategies, and the grid and PV system characteristics. These results serve as an example of the potential improvement in THD when employing the passive damping filter. The damping filter's resistive, inductive, and capacitive elements act harmoniously, dissipating and redirecting these undesirable harmonics. The results are a cleaner waveform, improved power quality, and reduced risks such as losses and equipment stress. The damping filter shows its effective role in enhancing system performance.

Table 2. Simulation of PV-microinverter at dynamic operation

Filter	(V_{out})	(I_{out})	(P_{out})	THD	T res	Effic
LCL	230V	1.44A	329.2W	10.08%	0.08s	94.4%
LCL+HB	230V	3.00A	690.0W	6.060%	0.02s	90.9%
LCL+PD	230V	3.23A	740.6W	3.730%	0.02s	93.3%

4. CONCLUSION

LCL and RLC damping filters are common in PV microinverters to improve power quality and minimize grid currents' harmonic distortion. LCL filter is known for providing superior attenuation of harmonic frequencies; however, it is also more expensive and can result in greater energy losses within the system. Furthermore, LCL filters effectively attenuate harmonic frequencies, but their design and adjustment require careful consideration and expertise due to their complexity. In contrast, the damping filter is simple; compared to LCL filters, this filter provides less attenuation of harmonic frequencies but is more cost-effective and incurs fewer losses.

Additionally, due to their simpler design and easier adjustability, damping filters are often a choice for small-scale PV microinverters. When considering performance, LCL filters are preferred for larger-scale PV systems as they provide superior harmonic filtering to meet grid interconnection standards. In contrast, damping filters can be suitable for smaller-scale systems where affordability and ease of use are critical.

The PD filter type is determined by the specific needs of the PV microinverter, including considerations like system size, grid connection requirements, and budgetary constraints. In some configurations, the LCL filter uses the damping filter to effectively address the THD issues in PV microinverters. The LCL filter is highly effective at reducing high-frequency harmonics; however, it may introduce resonance at certain frequencies, which can pose challenges. The damping filter is designed to mitigate this resonance by dampening low-frequency harmonics; this enhancement improves the overall performance of the filter and significantly decreases THD in the grid current. The resonance observed in the LCL filter arises from the interaction between the inductors and capacitors, potentially creating a high-Q (quality factor) resonance at specific frequencies. This resonance can amplify high-frequency harmonics and lead to voltage distortion.

A passive damping filter, consisting of a resistor (R), inductor (L), and capacitor (C), is often placed in parallel with an LCL filter to mitigate resonances. This setup offers a low-impedance path for low-frequency harmonics, effectively damping any resonances associated with the LCL filter. The resistor allows current to flow through the damping filter, dissipating energy and reducing the Q factor of the circuit.

Meanwhile, the inductor and capacitor provide frequency-dependent impedance, which helps to attenuate low-frequency harmonics. Together, these components enhance power quality and system stability.

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REFERENCES

[1] V. Vlatkovic, "Alternative energy: State of the art and implications on power electronics," in *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, 2004, vol. 1, pp. 45–50, doi: 10.1109/APEC.2004.1295786.
[2] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, "Renewable energy resources: Current status, future prospects and their enabling technology," *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 748–764, 2014, doi: 10.1016/j.rser.2014.07.113.
[3] J. M. Carrasco *et al.*, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1002–1016, 2006, doi: 10.1109/TIE.2006.878356.
[4] UNDP, "Goal 7: Affordable and clean energy," *undp.org.*, 2015. https://www.undp.org/sustainable-development-goals/affordable-and-clean-energy (accessed Sep. 07, 2024).
[5] A. R. Jordehi, "Maximum power point tracking in photovoltaic (PV) systems: A review of different approaches," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 1127–1138, 2016, doi: 10.1016/j.rser.2016.07.053.
[6] D. M. Scholten, N. Ertugrul, and W. L. Soong, "Micro-inverters in small scale PV systems: A review and future directions," in *2013 Australasian Universities Power Engineering Conference, AUPEC 2013*, 2013, pp. 1–6, doi: 10.1109/aupec.2013.6725465.
[7] S. Harb, M. Kedia, H. Zhang, and R. S. Balog, "Microinverter and string inverter grid-connected photovoltaic system - A comprehensive study," in *Conference Record of the IEEE Photovoltaic Specialists Conference*, 2013, pp. 2885–2890, doi: 10.1109/PVSC.2013.6745072.
[8] M. H. Todorovic *et al.*, "A multi-objective study for down selection of a micro-inverter topology for residential applications," in *2014 IEEE 40th Photovoltaic Specialist Conference, PVSC 2014*, 2014, pp. 3108–3113, doi: 10.1109/PVSC.2014.6925595.
[9] H. P. Ikkurti and S. Saha, "A comprehensive techno-economic review of microinverters for building integrated photovoltaics (BIPV)," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 997–1006, 2015, doi: 10.1016/j.rser.2015.03.081.
[10] M. Calais, J. Myrzik, T. Spooner, and V. G. Agelidis, "Inverters for single-phase grid connected photovoltaic systems - An overview," in *PESC Record - IEEE Annual Power Electronics Specialists Conference*, 2002, vol. 4, pp. 1995–2000, doi: 10.1109/psec.2002.1023107.
[11] S. Kumar.D, R. N. D. Indira, and R. Ashok, "Design and analysis of single phase grid connected inverter," *International Journal of Innovative Research in Computer and Communication Engineering (IJIRCCE)*, vol. 3, no. 2, pp. 1245–1251, 2015.
[12] H. Hu, S. Harb, N. Kutkut, I. Batarseh, and Z. J. Shen, "Power decoupling techniques for micro-inverters in PV systems-A review," in *2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings*, 2010, pp. 3235–3240, doi: 10.1109/ECCE.2010.5618285.
[13] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Transactions on Industry Applications*, vol. 41, no. 5, pp. 1292–1306, 2005, doi: 10.1109/TIA.2005.853371.
[14] S. Z. Mohammad Noor, A. M. Omar, N. N. Mahzan, and I. R. Ibrahim, "A review of single-phase single stage inverter topologies for photovoltaic system," in *Proceedings - 2013 IEEE 4th Control and System Graduate Research Colloquium, ICSGRC 2013*, 2013, pp. 69–74, doi: 10.1109/ICSGRC.2013.6653278.
[15] K. Alluhaybi, I. Batarseh, and H. Hu, "Comprehensive review and comparison of single-phase grid-tied photovoltaic microinverters," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 2, pp. 1310–1329, 2020, doi: 10.1109/JESTPE.2019.2900413.
[16] C. L. Trujillo, F. Santamaria, and E. E. Gaona, "Modeling and testing of two-stage grid-connected photovoltaic micro-inverters," *Renewable Energy*, vol. 99, pp. 533–542, 2016.
[17] R. Peña-Alzola, M. Liserre, F. Blaabjerg, R. Sebastían, J. Dannehl, and F. W. Fuchs, "Analysis of the passive damping losses in lcl-filter-based grid converters," *IEEE Transactions on Power Electronics*, vol. 28, no. 6, pp. 2642–2646, 2013, doi: 10.1109/TPEL.2012.2222931.
[18] C. Gurrola-Corral, J. Segundo, M. Esparza, and R. Cruz, "Optimal LCL-filter design method for grid-connected renewable energy sources," *International Journal of Electrical Power and Energy Systems*, vol. 120, p. 105998, Sep. 2020, doi: 10.1016/j.ijepes.2020.105998.
[19] A. Rani and G. Sharma, "Power quality improvement in grid connected PV system," *International Journal of Trend in Scientific Research and Development*, pp. 429–433, 2017, doi: 10.31142/ijtsrd2196.
[20] J. C. Das, "Passive filters: Potentialities and limitations," *IEEE Transactions on Industry Applications*, vol. 40, no. 1, pp. 232–241, 2004, doi: 10.1109/TIA.2003.821666.
[21] M. Liserre, R. Teodorescu, and F. Blaabjerg, "Stability of grid-connected PV inverters with large grid impedance variation," in *PESC Record - IEEE Annual Power Electronics Specialists Conference*, 2004, vol. 6, pp. 4773–4779, doi: 10.1109/PESC.2004.1354843.
[22] M. Jayaraman and V. T. Sreedevi, "Implementation of LC and LCL passive filters for harmonic reduction in PV based renewable energy systems," in *2017 National Power Electronics Conference, NPEC 2017*, 2017, vol. 2018-January, pp. 363–369, doi: 10.1109/NPEC.2017.8310486.
[23] IEEE Std 1159, "IEEE recommended practice for monitoring electric power quality," *IEEE Std 1159-2009 (Revision of IEEE Std 1159-1995)*, vol. 1995. pp. 1–94, 2009, doi: 10.1109/IEEESTD.2009.5154024.
[24] F. Li, X. Zhang, H. Zhu, H. Li, and C. Yu, "An LCL-LC filter for grid connected converter: topology, parameter, and analysis,"

IEEE Transactions on Power Electronics, vol. 30, no. 9, pp. 5067–5077, 2015.
[25] H. Hu, Q. Shi, Z. He, J. He, and S. Gao, "Potential harmonic resonance impacts of PV inverter filters on distribution systems," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 151–161, 2015, doi: 10.1109/TSTE.2014.2352931.
[26] C. Poongothai and K. Vasudevan, "Design of LCL filter for grid-interfaced PV system based on cost minimization," *IEEE Transactions on Industry Applications*, vol. 55, no. 1, pp. 584–592, 2019, doi: 10.1109/TIA.2018.2865723.
[27] G. E. M. Ruiz, N. Munoz, and J. B. Cano, "Modeling, analysis and design procedure of LCL filter for grid connected converters," in *2015 IEEE Workshop on Power Electronics and Power Quality Applications, PEPQA 2015 - Proceedings*, 2015, pp. 1–5, doi: 10.1109/PEPQA.2015.7168215.
[28] A. Reznik, M. G. Simoes, A. Al-Durra, and S. M. Muyeen, "LCL Filter design and performance analysis for grid-interconnected systems," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1225–1232, Mar. 2014, doi: 10.1109/TIA.2013.2274612.
[29] J. Jo, Z. Liu, and H. Cha, "A new design method of LCL filter for single phase grid connected power converter," in *Proceedings - 2019 International Symposium on Electrical and Electronics Engineering, ISEE 2019*, 2019, pp. 189–193, doi: 10.1109/ISEE2.2019.8921036.
[30] I. Bhattacharya, Y. Deng, and S. Y. Foo, "Active filters for harmonics elimination in solar Photovoltaic grid-connected and stand-alone systems," in *Proceedings of the 2nd Asia Symposium on Quality Electronic Design, ASQED 2010*, 2010, pp. 280–284, doi: 10.1109/ASQED.2010.5548252.
[31] A. C. Kyritsis, N. P. Papanikolaou, and E. C. Tatakis, "Enhanced current pulsation smoothing parallel active filter for single stage grid-connected AC-PV modules," in *2008 13th International Power Electronics and Motion Control Conference, EPE-PEMC 2008*, 2008, pp. 1287–1292, doi: 10.1109/EPEPEMC.2008.4635446.
[32] C. C. Gomes, A. F. Cupertino, and H. A. Pereira, "Damping techniques for grid-connected voltage source converters based on LCL filter: An overview," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 116–135, 2018, doi: 10.1016/j.rser.2017.07.050.
[33] Y. Du and D. D.-C. Lu, "Harmonic distortion caused by single-phase grid-connected PV inverter," in *Power System Harmonics - Analysis, Effects and Mitigation Solutions for Power Quality Improvement*, J. C. Hernandez, Ed. IntechOpen, 2018, doi: 10.5772/intechopen.73030.
[34] J. Xu and S. Xie, "LCL-resonance damping strategies for grid-connected inverters with LCL filters: a comprehensive review," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 2, pp. 292–305, 2018, doi: 10.1007/s40565-017-0319-7.
[35] H. M. Ahn, C. Y. Oh, W. Y. Sung, J. H. Ahn, and B. K. Lee, "Analysis and design of LCL filter with passive damping circuits for three-phase grid-connected inverters," *Journal of Electrical Engineering and Technology*, vol. 12, no. 1, pp. 217–224, 2016, doi: 10.5370/JEET.2016.12.1.217.
[36] S. Arulmurugan and A. Anbarasan, "Harmonics elimination in grid connected single phase PV inverter," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 3, no. 1, pp. 1473–1480, 2014, [Online]. Available: http://www.rroij.com/open-access/harmonics-elimination-in-grid-connected-singlephase-pv-inverter-.php?aid=51332
[37] R. N. Beres, X. Wang, F. Blaabjerg, M. Liserre, and C. L. Bak, "Optimal design of high-order passive-damped filters for grid-connected applications," *IEEE Transactions on Power Electronics*, vol. 31, no. 3, pp. 2083–2098, 2016, doi: 10.1109/TPEL.2015.2441299.
[38] L. Alhafadhi, J. Asumadu, and A. Alsafi, "Total harmonics distortion reduction using a new method of adaptive filtering," in *2016 IEEE Western New York Image and Signal Processing Workshop, WNYISPW 2016*, 2017, pp. 1–5, doi: 10.1109/WNYIPW.2016.7904791.
[39] M. Ayub, C. K. Gan, and A. F. A. Kadir, "The impact of grid-connected PV systems on Harmonic Distortion," in *2014 IEEE Innovative Smart Grid Technologies - Asia, ISGT ASIA 2014*, 2014, pp. 669–674, doi: 10.1109/ISGT-Asia.2014.6873872.
[40] T. Moyra, S. K. Parui, and S. Das, "Design and development of lowpass filter and harmonics reduction," *International Journal on Electrical Engineering and Informatics*, vol. 3, no. 3, pp. 336–349, 2011, doi: 10.15676/ijeei.2011.3.3.6.
[41] N. Shah, "Harmonics in power systems Causes, effects and control," *Whitepaper design engineering low-voltage drives*, 2013, pp. 1-23.
[42] M. Mirhosseini, J. Pou, and V. G. Agelidis, "Single- and two-stage inverter-based grid-connected photovoltaic power plants with ride-through capability under grid faults," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 1150–1159, 2015, doi: 10.1109/TSTE.2014.2347044.
[43] S. E. Babaa, G. El Murr, F. Mohamed, and S. Pamuri, "Overview of boost converters for photovoltaic systems," *Journal of Power and Energy Engineering*, vol. 06, no. 04, pp. 16–31, 2018, doi: 10.4236/jpee.2018.64002.
[44] P. J. Bhaskara Rao and B. Srikanth, "Harmonic reduction in grid connected solar PV system by using SVPWM technique," *International Journal of Applied Engineering Research*, vol. 11, no. 6, pp. 3853–3858, 2016.
[45] D. G. Holmes and T. A. Lipo, *Pulse width modulation for power converters*. John Wiley & Sons, 2010, doi: 10.1109/9780470546284.
[46] W. Wu, Y. He, T. Tang, and F. Blaabjerg, "A new design method for the passive damped LCL and LLCL filter-based single-phase grid-tied inverter," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 10, pp. 4339–4350, 2013, doi: 10.1109/TIE.2012.2217725.
[47] R. A. Fantino, C. A. Busada, and J. A. Solsona, "Optimum PR control applied to LCL filters with low resonance frequency," *IEEE Transactions on Power Electronics*, vol. 33, no. 1, pp. 793–801, 2018, doi: 10.1109/TPEL.2017.2667409.
[48] D. Pan, X. Ruan, X. Wang, H. Yu, and Z. Xing, "Analysis and design of current control schemes for LCL-type grid-connected inverter based on a general mathematical model," *IEEE Transactions on Power Electronics*, vol. 32, no. 6, pp. 4395–4410, 2017, doi: 10.1109/TPEL.2016.2602219.
[49] K. B. Park, F. Kieferndorf, U. Drofenik, S. Pettersson, and F. Canales, "Weight minimization of LCL filters for high power converters," in *9th International Conference on Power Electronics - ECCE Asia: "Green World with Power Electronics", ICPE 2015-ECCE Asia*, 2015, pp. 142–149, doi: 10.1109/ICPE.2015.7167778.
[50] N. Zhang, H. Tang, and C. Yao, "A systematic method for designing a PR controller and active damping of the LCL filter for single-phase grid-connected PV inverters," *Energies*, vol. 7, no. 6, pp. 3934–3954, 2014, doi: 10.3390/en7063934.
[51] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of three-phase improved power quality ac-dc converters," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 3, pp. 641–660, 2004, doi: 10.1109/TIE.2004.825341.
[52] Y. Teng, C. Xiong, C. Li, Q. Hui, and Y. Zhu, "Grid-connected PV power plant LCL filter based on PI and PR control strategy," in *Proceedings of 2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference, IAEAC 2015*, 2016, pp. 1191–1196, doi: 10.1109/IAEAC.2015.7428748.

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