

# HYBRID PASSIVE–ACTIVE FILTERING STRATEGY FOR HARMONIC SUPPRESSION IN GRID-INTERACTIVE SOLAR PHOTOVOLTAIC INVERTER SYSTEMS

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**Abstract** -The rapid integration of solar photovoltaic (PV) systems into modern power grids has significantly increased the use of power electronic converters, particularly grid-interactive inverters, leading to serious power quality concerns. Among these, harmonic distortion is a critical issue that affects system efficiency, reliability, and compliance with grid standards such as IEEE 519. Conventional harmonic mitigation techniques, including passive and active filters, have been widely explored; however, each approach presents inherent limitations. Passive filters are cost-effective and simple but lack adaptability and may introduce resonance, whereas active filters offer dynamic compensation but involve high cost and complex control strategies. In this context, hybrid passive–active filtering has emerged as a promising solution that combines the advantages of both methods. This review paper presents a comprehensive analysis of harmonic generation in PV inverter systems and critically examines various filtering techniques, with a particular focus on hybrid configurations. The study synthesizes recent literature to evaluate performance metrics such as Total Harmonic Distortion (THD), efficiency, and dynamic response. Furthermore, it identifies key research gaps, including the need for adaptive control strategies and real-time implementation. The review concludes that hybrid filtering strategies provide an optimal balance between performance, cost, and reliability, making them highly suitable for future grid-connected PV applications.

**Key Words:** Solar Photovoltaic (PV), Harmonic Distortion, Hybrid Filtering, Active Power Filter, Passive Filter, Power Quality

## 1. INTRODUCTION

### 1.1 Background

The global transition toward sustainable energy systems has accelerated the deployment of solar photovoltaic (PV) technologies, driven by increasing energy demand, environmental concerns, and supportive government policies. Grid-connected PV systems have become a dominant configuration due to their ability to supply clean energy directly to utility networks while enhancing energy security. As PV penetration increases, the interaction between distributed generation and the conventional grid

introduces new operational complexities, particularly in maintaining power quality and system stability (Blaabjerg et al., 2017).

In grid-interactive PV systems, power electronic inverters serve as the critical interface between the DC output of PV arrays and the AC grid. These inverters not only perform DC–AC conversion but also regulate voltage, frequency, and synchronization with the grid. However, due to high-frequency switching operations primarily through pulse-width modulation (PWM) inverters inherently introduce non-linearities that distort current and voltage waveforms (Teodorescu et al., 2011).

Consequently, harmonic distortion has emerged as a major issue in modern PV-integrated power systems. These harmonics propagate into the grid, affecting power quality, increasing losses, and potentially violating regulatory standards. With the rapid growth of inverter-based renewable systems, addressing harmonic distortion has become a critical research and engineering priority (Yang et al., 2018).

### 1.2 Power Quality Challenges in PV Systems

Power quality degradation is one of the most significant challenges associated with grid-connected PV systems. Harmonics generated by inverter switching and non-linear loads distort the sinusoidal waveform of voltage and current, leading to increased Total Harmonic Distortion (THD). This distortion results in additional power losses in transmission lines, transformers, and other electrical components due to increased RMS currents (Arrillaga and Watson, 2003).

Voltage distortion is another major concern, as it can cause malfunction of sensitive electronic equipment and reduce the reliability of protection systems. Harmonics also contribute to overheating in electrical devices, insulation failure, and electromagnetic interference. These issues collectively degrade system performance and operational lifespan. Furthermore, excessive harmonic levels can compromise grid stability, especially in systems with high renewable penetration, where inverter-based generation dominates (Guerrero et al., 2013).

Therefore, maintaining acceptable power quality levels is essential for ensuring safe, efficient, and reliable operation of PV-integrated power systems.

### 1.3 Need for Advanced Harmonic Mitigation

Traditional harmonic mitigation techniques, including passive and active filters, have been widely employed in power systems. Passive filters are simple and cost-effective but suffer from fixed compensation characteristics and susceptibility to resonance with grid impedance. Their performance is highly dependent on system conditions, making them unsuitable for dynamic environments such as PV systems with fluctuating generation (Das, 2004).

Active filters, on the other hand, provide dynamic compensation by injecting counteracting currents or voltages. While they offer superior harmonic mitigation performance, they require complex control algorithms and involve high initial costs and switching losses. These limitations restrict their large-scale deployment in cost-sensitive PV applications (Akagi, 2005).

To overcome these challenges, hybrid passive-active filtering has been proposed as an advanced solution. This approach combines the cost-effectiveness of passive filters with the adaptability of active filters, enabling efficient harmonic suppression across a wide frequency range while maintaining economic feasibility. The hybrid strategy is particularly suitable for modern PV systems operating under variable conditions.

### 1.4 Contribution of This Review Paper

This review paper provides a comprehensive synthesis of existing research on harmonic mitigation in grid-connected PV inverter systems, with a particular emphasis on hybrid passive-active filtering strategies. It critically examines various filtering techniques and evaluates their performance in terms of THD reduction, efficiency, cost, and dynamic response.

A comparative analysis of passive, active, and hybrid filtering approaches is presented to highlight their respective advantages and limitations. Furthermore, the review identifies key research gaps, including the lack of adaptive control strategies and limited real-time implementation studies.

By integrating insights from recent literature, this paper also outlines future research directions, such as the application of intelligent control techniques and integration with smart grid technologies. Overall, the study aims to provide a structured knowledge base for researchers and engineers working in the field of power quality improvement in PV systems.

## 2. FUNDAMENTALS OF HARMONICS IN GRID-CONNECTED PV SYSTEMS

### 2.1 Definition and Characteristics of Harmonics

Harmonics are defined as sinusoidal components of a waveform whose frequencies are integer multiples of the fundamental frequency (typically 50 Hz or 60 Hz). These components distort the ideal sinusoidal waveform, resulting in non-linear behavior of electrical systems. The extent of distortion is quantified using Total Harmonic Distortion (THD), which represents the ratio of the root mean square (RMS) value of harmonic components to that of the fundamental frequency (IEEE, 2014).

Mathematically, a distorted waveform can be expressed as the sum of the fundamental component and its harmonic components. Harmonics are typically classified into lower-order (e.g., 3rd, 5th, 7th) and higher-order harmonics, each contributing differently to system distortion. Lower-order harmonics generally have higher magnitudes and more severe impacts on system performance.

### 2.2 Sources of Harmonics in PV Systems

In grid-connected PV systems, harmonics primarily originate from inverter switching operations. PWM-based voltage source inverters generate high-frequency switching signals, which introduce harmonic components into the output waveform. The switching frequency and modulation technique significantly influence the harmonic profile (Holmes and Lipo, 2003).

Non-linear loads connected to the grid, such as rectifiers, variable frequency drives, and electronic appliances, further contribute to harmonic distortion by drawing non-sinusoidal currents. Additionally, grid disturbances such as voltage fluctuations, faults, and frequency deviations can introduce or amplify harmonic components.

The combined effect of these sources results in complex harmonic patterns that vary with operating conditions, making mitigation a challenging task.

### 2.3 Effects of Harmonics

The presence of harmonics in power systems leads to several adverse effects. Increased harmonic currents cause additional  $I^2R$  losses in conductors and transformers, reducing system efficiency. Harmonics also lead to overheating of equipment, which accelerates insulation degradation and shortens device lifespan (Dugan et al., 2012).

Moreover, harmonic distortion can interfere with the operation of protective relays and control systems, leading to incorrect tripping or failure during faults. Sensitive electronic equipment is particularly vulnerable to voltage distortion, which can result in malfunction or data errors.

Overall, harmonics degrade power quality, reduce reliability, and increase maintenance costs, highlighting the need for effective mitigation strategies.

## 2.4 Harmonic Standards and Grid Codes

To regulate harmonic distortion and ensure system reliability, several international standards have been established. The IEEE 519 standard specifies permissible limits for voltage and current harmonics in power systems, depending on system voltage levels and operating conditions (IEEE, 2014).

Similarly, the International Electrotechnical Commission (IEC) provides guidelines for harmonic emissions and testing procedures for electrical equipment. These standards define acceptable THD limits, typically restricting voltage THD to below 5% in most grid-connected systems.

Compliance with these standards is essential for maintaining power quality, preventing equipment damage, and ensuring compatibility between different components of the power system.

## 3. OVERVIEW OF HARMONIC MITIGATION TECHNIQUES

### 3.1 Passive Filtering Techniques

#### 3.1.1 Single-Tuned Filters

Single-tuned filters are designed to eliminate specific harmonic frequencies by creating a low-impedance path at the targeted frequency. These filters typically consist of inductors and capacitors configured to resonate at a particular harmonic order, such as the 5th or 7th.

They are widely used in industrial and PV applications due to their simplicity and cost-effectiveness. By diverting harmonic currents away from the main system, single-tuned filters effectively reduce dominant harmonic components.

#### 3.1.2 High-Pass Filters

High-pass filters are used for broadband harmonic mitigation, particularly for higher-order harmonics. These filters allow high-frequency components to pass through while blocking the fundamental frequency.

They are often used in combination with single-tuned filters to achieve comprehensive harmonic suppression across a wide frequency range. Their ability to address multiple harmonics makes them suitable for complex systems with diverse harmonic profiles.

#### 3.1.3 Advantages and Limitations

Passive filters offer several advantages, including low cost, simple design, and ease of implementation. However, they

also have significant limitations. Their performance is fixed and dependent on system parameters, making them unsuitable for dynamic conditions.

Additionally, passive filters are prone to resonance with grid impedance, which can amplify harmonics instead of suppressing them. These limitations restrict their effectiveness in modern PV systems with variable operating conditions (Das, 2004).

## 3.2 Active Filtering Techniques

### 3.2.1 Shunt Active Power Filters (SAPF)

Shunt Active Power Filters are widely used for current harmonic compensation. They are connected in parallel with the load and inject compensating currents to cancel harmonic components.

SAPFs provide dynamic and real-time harmonic mitigation, making them highly effective in systems with fluctuating loads and renewable energy sources. They also improve power factor and load balancing.

### 3.2.2 Series Active Power Filters

Series Active Power Filters are primarily used for voltage harmonic compensation. They are connected in series with the power system and inject compensating voltages to maintain waveform quality.

These filters are particularly useful for protecting sensitive loads from voltage distortion and disturbances. However, their complexity and higher cost limit their widespread application compared to shunt active filters (Akagi, 2005).

## 4. HYBRID PASSIVE-ACTIVE FILTERING STRATEGIES

### 4.1 Concept and Operating Principle

Hybrid passive-active filtering strategies are developed to overcome the inherent limitations of standalone passive and active filters by combining their complementary advantages. In this approach, passive filters—typically LC-based—are employed to suppress dominant lower-order harmonics, while active power filters (APFs) are used to dynamically compensate for higher-order harmonics and system variations. This coordinated operation enables efficient harmonic mitigation across a broad frequency spectrum while reducing the computational and power burden on the active filter (Peng, 2001).

The fundamental operating principle of hybrid filters lies in the division of harmonic compensation tasks. Passive filters provide a low-impedance path for specific harmonic frequencies, thereby diverting significant harmonic currents away from the grid. Meanwhile, the active filter continuously monitors system conditions and injects compensating

currents or voltages to eliminate residual harmonics and maintain waveform quality. This dual-action mechanism ensures improved power quality and system stability under both steady-state and dynamic conditions (Rahmani et al., 2010).

## 4.2 Classification of Hybrid Filters

### 4.2.1 Shunt Hybrid Filters

Shunt hybrid filters are the most commonly used configuration in grid-connected PV systems. In this arrangement, both passive and active filters are connected in parallel with the load. The passive filter handles bulk harmonic elimination, particularly lower-order harmonics, while the shunt active filter injects compensating currents to cancel higher-order harmonics and correct power factor. This configuration is highly effective for current harmonic mitigation and is widely adopted due to its relatively simple structure and high efficiency (Singh et al., 1999).

### 4.2.2 Series Hybrid Filters

Series hybrid filters are connected in series with the power system and are primarily used for voltage harmonic compensation. In this configuration, the active filter injects compensating voltage to counteract distortion, while the passive filter supports harmonic attenuation. These filters are particularly suitable for protecting sensitive loads from voltage disturbances and improving voltage quality. However, their application is less common due to increased system complexity and higher implementation cost (Fujita and Akagi, 1991).

### 4.2.3 Series-Shunt Hybrid Configurations

Series-shunt hybrid configurations combine both shunt and series filtering mechanisms to achieve comprehensive harmonic mitigation. In this topology, the shunt component addresses current harmonics, while the series component mitigates voltage harmonics. Such configurations are capable of providing superior compensation performance, especially in complex power systems with both current and voltage distortions. Despite their effectiveness, their practical implementation is limited by higher cost and control complexity, requiring advanced coordination strategies (Akagi, 2005).

## 4.3 Performance Characteristics

Hybrid filtering strategies demonstrate superior performance characteristics compared to standalone filtering approaches. One of the most significant advantages is the substantial reduction in Total Harmonic Distortion (THD), often achieving levels well within regulatory limits. By distributing harmonic compensation between passive and active components, hybrid filters effectively suppress both low-order and high-order harmonics (Zhang et al., 2016).

In addition to THD reduction, hybrid filters exhibit enhanced stability under dynamic operating conditions such as load variations and fluctuating solar irradiance. The active component enables real-time adaptation, ensuring consistent performance even in rapidly changing environments. Furthermore, hybrid filters offer an optimal cost-performance trade-off. Since the passive filter handles a significant portion of harmonic mitigation, the required rating of the active filter is reduced, resulting in lower overall system cost and improved efficiency.

## 4.4 Advantages over Conventional Methods

Hybrid passive-active filters provide several advantages over conventional filtering techniques. Firstly, they improve system efficiency by minimizing harmonic losses and reducing stress on electrical components. The division of harmonic compensation tasks ensures efficient utilization of both passive and active elements (El-Habrouk et al., 2000).

Secondly, hybrid filters significantly reduce the required rating of the active power filter, which lowers capital cost and switching losses. This makes the system more economically viable for large-scale PV applications. Additionally, hybrid filters offer better adaptability compared to passive filters, as the active component dynamically responds to system variations. This adaptability ensures reliable operation under diverse operating conditions, making hybrid filtering a preferred solution for modern grid-integrated renewable systems.

## 5. LITERATURE REVIEW

### 5.1 Review of Passive Filtering-Based Studies

Extensive research has been conducted on passive filtering techniques for harmonic mitigation in power systems. Early studies focused on the design and optimization of single-tuned and high-pass filters to suppress dominant harmonic components. These studies demonstrated that passive filters can effectively reduce THD levels, particularly for lower-order harmonics, with relatively low implementation cost (Arrillaga et al., 2000).

However, subsequent research identified several limitations associated with passive filters. Their performance is highly dependent on system impedance, and they are prone to resonance issues that can amplify harmonic distortion. Additionally, passive filters lack adaptability, making them less effective under dynamic operating conditions such as varying loads and renewable generation (Das, 2004). These limitations have driven the exploration of more advanced filtering techniques.

## 5.2 Review of Active Filtering-Based Studies

Active filtering techniques have gained significant attention due to their dynamic and flexible harmonic compensation capabilities. Research on shunt active power filters (SAPFs) has shown that they can achieve substantial THD reduction by injecting compensating currents in real time. Advances in control strategies, such as instantaneous power theory (p-q theory) and synchronous reference frame (d-q theory), have further improved the accuracy and response speed of active filters (Akagi et al., 2007).

Recent studies have also explored advanced control methods, including predictive control and adaptive algorithms, to enhance performance under dynamic conditions. While active filters provide superior harmonic mitigation, their high cost, complexity, and switching losses remain significant challenges, limiting their widespread adoption in cost-sensitive applications (Bhattacharya and Divan, 1995).

## 5.3 Review of Hybrid Filtering Approaches

Hybrid filtering approaches have emerged as a promising solution that integrates the advantages of both passive and active filters. Recent studies have proposed various hybrid configurations for grid-connected PV systems, demonstrating significant improvements in harmonic suppression and system efficiency. These designs typically achieve lower THD levels compared to standalone filters while reducing the required rating of the active filter (Rahmani et al., 2010).

Comparative analyses in the literature indicate that hybrid filters provide a balanced solution in terms of performance, cost, and complexity. They are particularly effective in dynamic environments where harmonic profiles vary due to changing load and generation conditions. As a result, hybrid filtering has become a key focus area in modern power quality research.

## 6. ROLE OF INVERTER TOPOLOGY AND CONTROL IN HARMONIC MITIGATION

### 6.1 Impact of Inverter Topologies

The inverter topology plays a decisive role in determining the harmonic profile of grid-connected solar photovoltaic (PV) systems. Conventional two-level voltage source inverters (VSIs) are widely used due to their simple structure and ease of control; however, they inherently generate higher harmonic distortion because the output voltage switches between only two levels. This results in steep voltage transitions and increased reliance on external filtering to achieve acceptable Total Harmonic Distortion (THD).

In contrast, multilevel inverters (MLIs) have emerged as an advanced alternative for harmonic mitigation. These inverters produce multiple voltage levels, which approximate a sinusoidal waveform more closely than traditional VSIs. As a result, the harmonic content in the output is significantly reduced even before filtering is applied. Additionally, MLIs reduce voltage stress on switching devices and improve overall efficiency. However, their increased number of components and control complexity present design and implementation challenges. Therefore, the choice of inverter topology directly influences the extent of harmonic mitigation required and the effectiveness of subsequent filtering strategies.

### 6.2 Modulation Techniques

Modulation techniques are critical in shaping the output waveform of inverters and thereby controlling harmonic generation. Sinusoidal Pulse Width Modulation (SPWM) is one of the most commonly used techniques, where a sinusoidal reference signal is compared with a high-frequency carrier waveform to generate switching pulses. SPWM is simple and effective but produces relatively higher harmonic distortion compared to more advanced techniques.

Space Vector Pulse Width Modulation (SVPWM), on the other hand, offers improved performance by utilizing the space vector representation of inverter switching states. SVPWM optimizes switching sequences to maximize DC bus utilization and reduce harmonic distortion. It also results in lower switching losses and better voltage quality compared to SPWM.

The selection of modulation technique has a direct impact on harmonic content, switching losses, and overall system efficiency. Advanced modulation strategies are often preferred in modern PV systems to minimize harmonics at the source, thereby reducing the burden on filtering systems.

### 6.3 Smart and Adaptive Control Techniques

With increasing system complexity and variability in operating conditions, conventional control methods are often insufficient for effective harmonic mitigation. Smart and adaptive control techniques have been developed to enhance system performance and adaptability. Artificial intelligence (AI)-based control methods, such as neural networks and fuzzy logic controllers, enable real-time decision-making by learning system behavior and adjusting control actions accordingly. These methods improve harmonic compensation accuracy and system robustness under uncertain conditions.

Predictive control techniques further enhance performance by forecasting system behavior and applying optimal control actions in advance. Model predictive control (MPC), for instance, minimizes harmonic distortion while optimizing switching performance and system constraints. Adaptive

filtering techniques continuously adjust control parameters based on system dynamics, ensuring effective harmonic mitigation even under fluctuating load and generation conditions.

These advanced control strategies significantly improve the effectiveness of hybrid filtering systems by enabling precise, fast, and adaptive harmonic compensation.

## 7. INTEGRATION OF HYBRID FILTERS IN PV SYSTEMS

### 7.1 Placement Strategies

The placement of hybrid filters within a grid-connected PV system significantly influences their performance and effectiveness. Inverter-side placement involves installing the filter directly at the output of the inverter, where harmonic generation primarily occurs. This approach ensures that harmonics are mitigated before being injected into the grid, resulting in improved waveform quality and reduced stress on downstream components.

Alternatively, grid-side placement positions the filter at the point of common coupling (PCC), where it can address harmonics originating from both the PV system and other connected loads. This approach is beneficial in systems with multiple harmonic sources, as it provides centralized compensation. However, it may require higher filter capacity and more complex coordination.

The choice between inverter-side and grid-side placement depends on system configuration, harmonic sources, and economic considerations. In many practical applications, inverter-side filtering is preferred due to its targeted mitigation capability and lower implementation complexity.

### 7.2 System-Level Considerations

The integration of hybrid filters must account for several system-level considerations, including stability, efficiency, and cost. Stability is a critical factor, as improper filter design or interaction with grid impedance can lead to resonance and system oscillations. Hybrid filters improve stability by combining passive damping with active control, ensuring reliable operation under dynamic conditions.

Efficiency is another key consideration, as harmonic distortion contributes to additional losses in electrical components. By reducing harmonics, hybrid filters enhance overall system efficiency and improve energy utilization. Furthermore, the reduced rating of the active filter component minimizes switching losses, contributing to higher system performance.

Cost plays a significant role in practical implementation. While active filters alone are expensive, the hybrid approach reduces overall cost by utilizing passive components for bulk harmonic mitigation. This cost-performance balance makes

hybrid filtering an attractive solution for large-scale PV installations.

### 7.3 Practical Implementation Challenges

Despite their advantages, the practical implementation of hybrid filtering systems presents several challenges. One of the primary issues is hardware complexity, particularly in systems involving multilevel inverters and advanced control schemes. The integration of passive and active components requires careful design to avoid resonance and ensure coordinated operation.

Control synchronization is another critical challenge, as the active filter must operate in harmony with the passive filter and the inverter control system. Any mismatch or delay in control signals can reduce compensation effectiveness and lead to instability. Additionally, real-time implementation requires high-speed processors and accurate sensing mechanisms, increasing system complexity and cost.

Addressing these challenges requires robust design methodologies, advanced control algorithms, and careful system integration. Overcoming these limitations is essential for the successful deployment of hybrid filtering strategies in practical PV systems.

## 8. CONCLUSION

This review paper has presented a comprehensive analysis of harmonic mitigation in grid-interactive solar photovoltaic (PV) inverter systems, with a particular emphasis on hybrid passive-active filtering strategies. The study began by examining the fundamental causes of harmonic distortion, primarily arising from inverter switching operations, non-linear loads, and grid disturbances. It was observed that harmonic distortion significantly degrades power quality, leading to increased losses, reduced efficiency, and potential malfunction of electrical equipment.

A critical evaluation of conventional mitigation techniques revealed that passive filters, although economical and simple, suffer from lack of adaptability and resonance issues, while active filters provide dynamic compensation but involve high cost and complexity. In this context, hybrid filtering strategies were identified as a superior solution, effectively combining the strengths of both approaches. The hybrid system distributes harmonic compensation tasks, enabling efficient suppression of both lower-order and higher-order harmonics while reducing the required rating of the active power filter.

Furthermore, the role of inverter topology, modulation techniques, and advanced control strategies in minimizing harmonic generation was highlighted. The integration aspects of hybrid filters, including placement and system-level considerations, were also discussed to ensure optimal performance. Overall, the review concludes that hybrid passive-active filtering provides an optimal balance between

performance, cost, and adaptability, making it a highly suitable solution for modern grid-connected PV systems and future smart grid applications.

## 9. FUTURE SCOPE OF RESEARCH

Future research can focus on the development of intelligent hybrid filtering systems using artificial intelligence and machine learning techniques to enhance adaptability and real-time performance. The implementation of advanced control strategies, such as predictive and adaptive algorithms, can further improve harmonic compensation under dynamic conditions.

Additionally, experimental validation through hardware prototypes is essential to bridge the gap between simulation and practical implementation. Integration of hybrid filters with smart grid technologies, IoT-based monitoring systems, and energy storage solutions can enhance system reliability and efficiency.

Further studies may also explore optimized multilevel inverter topologies and cost-effective filter designs to improve scalability. Expanding research toward large-scale distributed generation systems and microgrids will be crucial for future renewable energy integration.

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