

Active Power Filters For Power Quality Enhancement In Microgrid Due To Renewable Energy Integration: A Review

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Abstract: The rising energy demand in residential and industrial sectors has accelerated the deployment of distributed generation systems, particularly photovoltaic (PV) and wind energy conversion systems (WECS). While these renewable sources offer environmental and economic benefits, their grid integration introduces power quality challenges such as harmonic distortion, reactive power imbalance, voltage fluctuations, and switching losses associated with power electronic converters. These issues adversely impact system efficiency, equipment lifespan, and overall grid reliability. Conventional passive filters provide limited dynamic compensation and are sensitive to grid variations. To address these limitations, active power filters (APFs) and hybrid active power filters (HAPFs) have gained prominence, with shunt APFs recognized for effective harmonic mitigation and reactive power control. Recent research emphasizes reducing switching device count, improving efficiency, and adopting transformer-less and multilevel inverter configurations to achieve compact and high-performance designs. This paper reviews key power quality issues in grid-connected PV and WECS systems, evaluates basic and advanced APF topologies, and discusses control strategies and implementation considerations. Potential research directions are highlighted to support the development of cost-effective and reliable APF solutions for future renewable-integrated power networks.

Keywords: microgrid, power quality, hybrid active power filters, active power filters, etc.

I.INTRODUCTION:

In recent years, the demand for electrical energy has been rapidly increasing across residential and industrial sectors, resulting in reduced energy reserves and frequent grid outages. To enhance power generation efficiency, reliability, and sustainability, distributed generation systems have gained significant importance [1][2]. These systems include photovoltaic (PV) installations, optimization-based control methods, energy storage units, wind turbines, fuel cells, and other distributed power technologies. Among these, PV and wind energy play a major role in reducing dependence on conventional utility grids and minimizing environmental impact. However, integrating PV and wind systems into the grid introduces challenges such as harmonic distortion, heating, and power quality degradation. These issues alter the waveform of current and voltage, negatively affecting system performance and causing problems such as transformer overheating, motor and cable failures, and increased power losses[3]. To ensure reliable grid operation, harmonic mitigation and power quality enhancement techniques are essential. Several methods have been proposed to address power quality issues, including solutions for unbalanced grid conditions, harmonic injection, neutral current compensation, reactive power management, and equipment protection [4-6]. Although passive filters are commonly used in grid-connected systems to mitigate harmonic distortion, they suffer from limitations such as fixed compensation range, bulky size, sensitivity to grid impedance variations, and reduced effectiveness under dynamic load conditions[7][8]. To overcome these limitations, advanced filtering technologies have been explored, including static synchronous compensators, active power filters (APFs), dynamic voltage restorers, multilevel

inverters, and coordinated power quality control systems. Among these, the shunt active power filter (SAPF) is widely preferred due to its flexibility and effective harmonic compensation capability as discussed in Fig. 1.



Fig. 1. Subdivision of power filter based on power rating and speed of response.

The performance of APFs depends on current sensing accuracy, inverter design, and control strategies[9]. Harmonic identification techniques are employed to generate the required reference signals, and their performance is guided by international standards such as IEEE-519 and IEC 61000-3-2. As load demands and power compensation requirements increase, the cost and rating of SAPF systems also rise. To address this, hybrid active power filters (HAPFs) have been introduced, combining SAPF with passive filters to handle both low- and high-frequency harmonics effectively. These hybrid solutions enhance harmonic compensation, reduce disturbances, and improve overall system response and power quality [10-13]. Here is a clearer, concise, and well-structured rephrased version: Transformer-less topologies have gained attention due to their ability to provide cleaner and more stable output, reduced system

size, lower cost, and enhanced compactness compared to conventional transformer-based designs. The overall system cost is influenced by factors such as galvanic isolation, variations in input-to-ground voltage, safety considerations, transmission losses, and system efficiency. In modern power networks, AC power is used for transmission and loads, while renewable sources typically supply DC power. Therefore, in both standalone and grid-connected renewable energy systems, an inverter is required to convert DC to AC and produce a high-quality sinusoidal output. Inverters are widely used across various power ranges from kilowatt scale to megawatt scale in large PV and wind installations. However, power electronic switches such as IGBTs and MOSFETs introduce challenges, including switching losses, harmonic distortions, and reduced overall efficiency. To enhance power quality and reduce current harmonics, shunt active power filters (SAPFs) are employed. Yet, increasing grid integration leads to more semiconductor switches, resulting in higher switching losses and further efficiency decline. Recent advances in power electronics, including improved semiconductor devices, control circuits, and sensor technologies, have focused on reducing the number of switching components. Although minimizing components is essential, limited research specifically addresses switch-count reduction in APFs [14]. Existing studies indicate progress toward reducing component count while improving inverter cost, size, and weight in grid-connected renewable energy systems.

For PV-based APFs and wind energy conversion systems (WECS), ongoing research includes module reduction, inverter minimization, and multi-level multifunctional inverter (ML-MFI) designs. Compared to conventional THD-oriented topologies, newer configurations provide better harmonic suppression, enhanced active and reactive power control, and improved overall performance. However, more work is needed to develop and validate switching-reduction strategies.

The structure of this paper is as follows: Section 1 provides an introduction. Section 2 discusses power quality issues in grid-connected PV and WECS systems. Section 3 explains the basic and recent APF topologies and their key characteristics. Sections 4 presents conclusions and future research directions.

Power Quality Issues In Grid-Connected Pv And Wecs Systems

The deployment of photovoltaic (PV) and wind energy conversion systems (WECS) in modern power grids has expanded considerably in response to the increasing need for environmentally friendly and sustainable energy solutions.

However, the inherently intermittent nature of solar and wind resources introduces significant variations in the generated power. Since PV output depends on solar irradiance and temperature, and wind turbines rely on fluctuating wind speeds, these variations can lead to voltage instability and frequency deviations, affecting the overall reliability and quality of the electrical grid.

A prominent power quality concern in such renewable-based systems is harmonic distortion, primarily caused by the power electronic converters and inverters used for DC-AC conversion and grid synchronization. These devices inject non-linear currents, resulting in distorted voltage and current waveforms. Increased harmonic levels lead to transformer overheating, reduced motor efficiency, malfunctioning of protection equipment, and accelerated aging of sensitive electronic devices. Therefore, adherence to standards such as IEEE-519 and IEC 61000-3 is essential to keep total harmonic distortion (THD) within permissible limits. Another critical issue is reactive power compensation and power factor correction. PV and wind systems typically do not supply reactive power on their own, and a lack of appropriate compensation may cause voltage instability and difficulties in maintaining the required power factor.

Moreover, fluctuating renewable power and load variations may result in unbalanced power flow, voltage flicker, and frequency instability. These effects are more pronounced in weak or rural grids with limited short-circuit capacity. Additionally, problems such as neutral current imbalance, grounding challenges, and transient overvoltages frequently arise, especially in transformer-less and three-phase inverter-based systems. These issues increase thermal stress on components, reduce equipment lifespan, and elevate maintenance costs.

To mitigate these challenges and enhance power quality, advanced solutions such as active power filters (APFs), hybrid filtering approaches, static synchronous compensators (STATCOM), and multifunctional inverter schemes are being investigated. In conclusion, although PV and WECS systems provide promising alternatives to conventional power sources, their integration into the grid brings forth several power quality concerns. Employing proper compensation mechanisms, advanced control strategies, and optimized converter designs is essential to ensure enhanced stability, efficiency, and reliability of renewable-integrated power networks.

Basic and recent APF topologies and their key characteristics

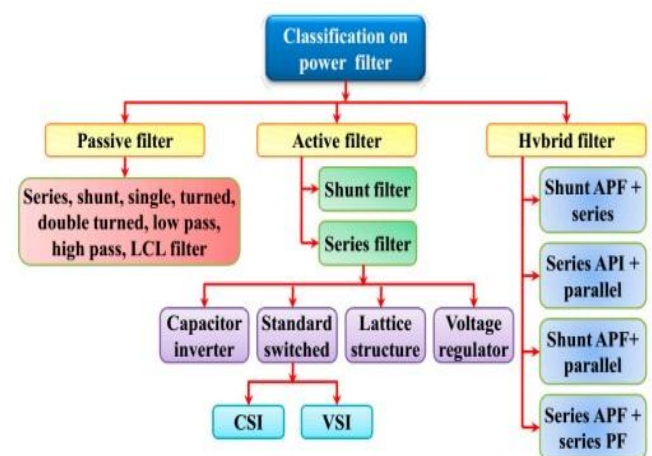


Fig. 2. Subdivision of Power Filters.

The configuration, converter type, and operating stages of active

power filters (APFs) are generally classified as shown in Figure 2. These are grouped into three main categories: Shunt Active Power Filters (SAPFs), Series Active Power Filters (APFs), and Hybrid Active Power Filters (HAPFs). The phase configurations may include single-phase (two-wire), three-phase (three-wire), or three-phase four-wire systems.

Figure 3 illustrates the three topology-based subclasses: shunt, series, and hybrid arrangements. Series APFs improve the quality of power at the supply terminals by minimizing the spread of harmonic voltages, which often result from system resonance. However, due to the increasing demand for high-current applications, available filter ratings and sizes remain limited. Three representative HAPF circuit configurations are also shown in Figure 3. In medium-voltage applications, a series APF combined with a shunt passive filter provides strong insulation and ensures reactive power compensation, voltage regulation, and harmonic mitigation in three-phase systems (Figure 3c).

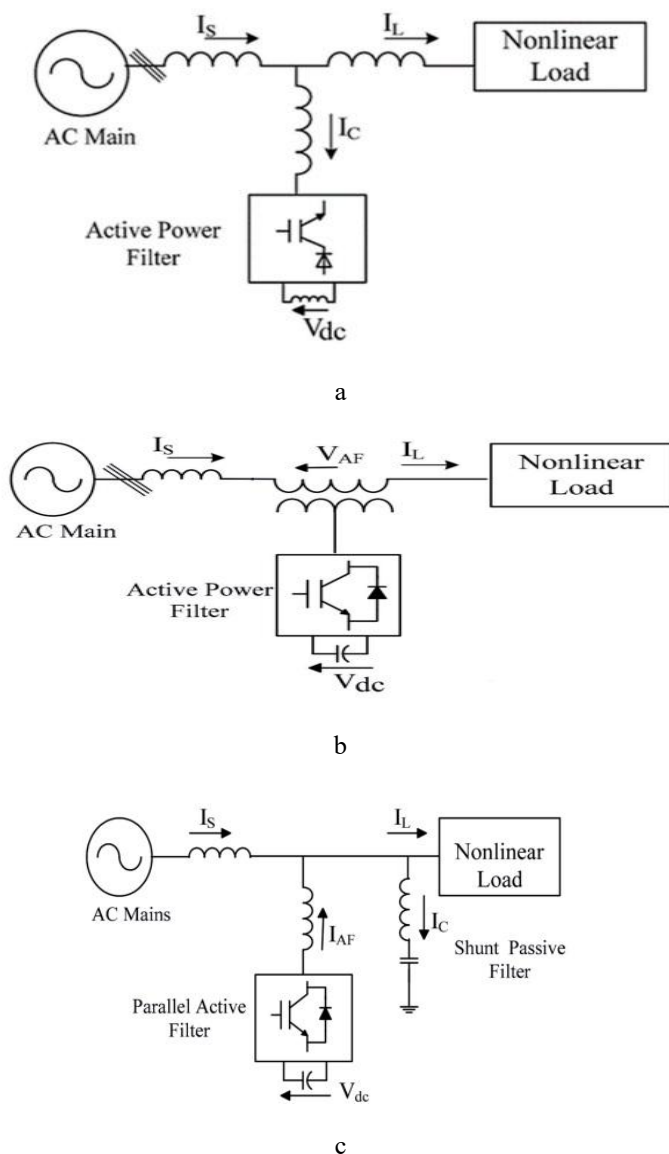


Fig. 3. Shunt APF, (b) series APF, and (c) hybrid APF

Similarly, SAPF used together with a shunt passive filter (Figure

3b) effectively compensates reactive power and suppresses harmonic currents in single-phase and load-current scenarios. These hybrid solutions reduce switching losses and lower the cost of reactive power compensation while maintaining high performance. Likewise, a series APF combined with a shunt passive filter (Figure 3a) helps maintain a stable DC-link voltage and consistent grid voltage in medium- and high-voltage systems, while reducing overall system volume and cost. However, traditional shunt APF configurations still face limitations such as higher energy losses and the need for large capacitor ratings.

II.CONCLUSION :

The integration of PV and WECS into modern power networks is essential for sustainable energy generation, yet it introduces power quality issues such as harmonic distortion, reactive power imbalance, and voltage fluctuations due to the use of power electronic converters. These disturbances affect grid stability and reduce the efficiency and lifespan of electrical equipment. Passive filters offer simple compensation but lack adaptability under varying operating conditions. Active Power Filters (APFs), especially shunt APFs, provide better dynamic performance and effective harmonic mitigation, while Hybrid APFs (HAPFs) combine the benefits of passive and active filtering to enhance system efficiency and reduce switching losses. Recent improvements in converter design, control algorithms, and semiconductor technology have contributed to more compact and efficient filtering solutions. However, challenges remain in reducing switching devices, improving reliability, and lowering implementation cost.

Future research should focus on advanced control strategies, multilevel APF structures, and coordinated compensation methods for distributed renewable systems. Ensuring high power quality is critical for stable and efficient operation of renewable-integrated power grids.

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