RESEARCH PAPER

A Three-Layer Renewable-Integrated Shunt Active Power Filter for Harmonic Mitigation and DC-Link Voltage Stabilization in Nonlinear Grid Systems

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Abstract

The increasing penetration of nonlinear loads and renewable energy sources in modern power systems has intensified power quality challenges such as current harmonics, reactive power demand, poor power factor, and DC-link voltage instability. This paper presents a comprehensive three-layer architecture for a renewable-integrated Shunt Active Power Filter (SAPF) designed to address these challenges in a unified framework. The proposed system combines a physical power stage for harmonic compensation, an intelligent control stage for accurate reference current generation and tracking, and an energy-management layer that integrates renewable energy sources through a regulated DC-link. The control strategy employs fundamental component extraction, harmonic isolation, reference current synthesis, and closed-loop current control to ensure effective harmonic mitigation and reactive power compensation. A renewable-assisted DC-link with PI-controlled DC–DC conversion is incorporated to maintain voltage stability under dynamic power conditions. MATLAB-based simulation results demonstrate a significant reduction in source current total harmonic distortion, improvement in power factor towards unity, and stable DC-link voltage regulation with limited overshoot and low steady-state error. The integrated performance confirms compliance with power quality standards and highlights the effectiveness of the proposed architecture for grid-connected systems with renewable energy support.

Keywords : Shunt Active Power Filter, Harmonic Compensation, Renewable Energy Integration, DC-Link Voltage Control, Power Quality Improvement, PI Control

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1. INTRODUCTION

The rapid growth of power electronic devices, nonlinear industrial loads, and renewable energy penetration has significantly altered the operating characteristics of modern electrical power systems. While these technologies improve efficiency and controllability, they also introduce severe power quality issues such as current harmonics, reactive power imbalance, voltage distortion, and reduced power factor at the point of common coupling (PCC) [1]. These problems not only degrade system efficiency but also cause excessive losses, overheating of equipment, malfunction of sensitive devices, and violation of international power quality standards such as IEEE-519 [2].

Nonlinear loads including diode rectifiers, adjustable speed drives, switched-mode power supplies, and industrial converters draw non-sinusoidal currents from the grid, leading to harmonic pollution in distribution networks [3]. Traditional passive filtering techniques have been widely used to mitigate harmonics; however, they suffer from drawbacks such as fixed compensation characteristics, resonance problems, bulky size, and poor performance under varying load conditions [4]. As a result, active power filtering techniques have emerged as a more flexible and adaptive solution for harmonic compensation and reactive power control [5].

Among active filtering approaches, the Shunt Active Power Filter (SAPF) has gained considerable attention due to its ability to compensate current harmonics, reactive power, and load imbalance simultaneously by injecting appropriate compensating currents into the system [6]. The effectiveness of an SAPF primarily depends on accurate reference current generation, fast current tracking capability, and stable DC-link voltage regulation [7]. Various control strategies such as instantaneous reactive power theory, synchronous reference frame theory, and predictive control have been proposed to enhance SAPF performance [8]. However, maintaining a stable DC-link voltage under dynamic load and grid conditions remains a critical challenge, especially when the SAPF operates under fluctuating compensation demands [9].

In recent years, the integration of renewable energy sources such as photovoltaic and wind systems into active power filtering structures has attracted growing research interest [10]. Renewable-integrated SAPF architectures not only improve power quality but also utilize available renewable power to support the DC-link energy requirement, thereby reducing dependence on the grid and improving overall system efficiency [11]. Nevertheless, improper coordination between harmonic compensation control and renewable energy management can lead to DC-link voltage oscillations, reduced compensation accuracy, and instability under transient conditions [12].

Motivated by these challenges, this paper proposes a comprehensive three-layer architecture for a renewable-integrated SAPF system. The first layer focuses on the physical power stage responsible for harmonic current compensation and grid interaction. The second layer implements an advanced control stage for fundamental component extraction, harmonic isolation, and accurate reference current generation with effective current tracking. The third layer introduces a renewable-assisted DC-link energy management scheme using a PI-controlled DC–DC converter to ensure stable DC-link voltage regulation under varying load and renewable power conditions. The proposed approach aims to achieve simultaneous harmonic mitigation, power factor improvement, and DC-link voltage stabilization in a unified and coordinated manner.

2. METHODOLOGY

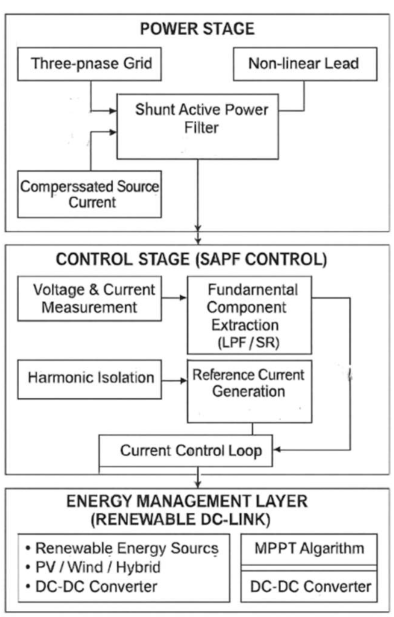

Figure 1: Three-Layer Methodology for SAPF-Based Power Quality Enhancement

This figure illustrates a three-layer methodology that integrates the physical power system, the SAPF control mechanism, and the renewable-energy-supported DC-link into a unified operational framework. At the top, the power stage represents the real electrical environment in which the three-phase grid supplies voltage to a non-linear load that introduces harmonic distortion and reactive power components. The Shunt Active Power Filter (SAPF) is connected in parallel at the point of common coupling, where it injects compensating current so that the resulting source current becomes cleaner and more sinusoidal. This physical layer shows how grid voltage, distorted load current, and SAPF compensation interact to produce an improved, compensated source current.

Beneath this, the control stage forms the computational core that enables the SAPF to operate intelligently. Measured voltages and currents are processed to extract the fundamental component using techniques such as LPF or synchronous reference frame transformation. Harmonic components are isolated, and a reference compensating current is generated to counteract the unwanted distortion produced by the non-linear load. A current control loop then ensures that the SAPF inverter accurately tracks this reference so that the injected current effectively cancels the harmonic and reactive components present in the load current. This stage captures the signal-processing and control algorithms that govern real-time compensation.

The bottom layer represents the renewable-energy-based DC-link management system that powers the SAPF. A renewable source—such as photovoltaic, wind, or hybrid energy—is interfaced through MPPT and a DC-DC converter to maintain a stable DC-link voltage. This regulated DC-link supports the inverter switches of the SAPF, enabling continuous and reliable current injection even under dynamic system conditions. Together, these three layers depict a coordinated methodology in which the electrical system, control algorithms, and renewable energy integration work cooperatively to achieve improved power quality and efficient harmonic compensation.

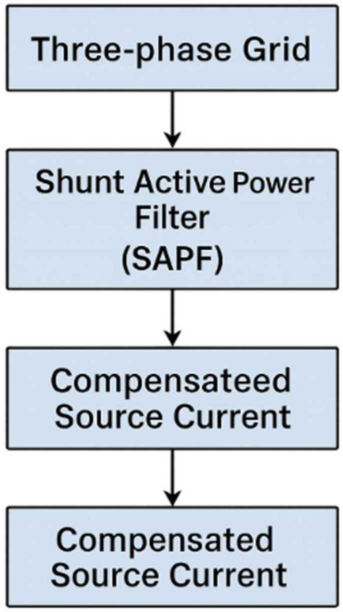

Figure 2: Power Stage

The Power Stage shown in figure 2 represents the physical electrical system in which the Shunt Active Power Filter (SAPF) operates. It includes the three-phase grid, the non-linear load, the SAPF injection point, and the resulting compensated source current delivered back to the grid. Understanding the mathematical model of each component is essential for developing the control and compensation strategy used in upper layers.

1. Three-Phase Grid Voltage Model

The three-phase utility grid is modeled as a balanced sinusoidal voltage source:

va(t) = Vm sin(ωt)

vb(t) = Vm sin(ωt − 2π/3)

vc(t) = Vm sin(ωt + 2π/3)

where Vm = √2 * VLN,rms, and ω = 2πf.

2. Non-linear Load Current

Non-linear loads draw distorted currents that can be expressed using Fourier series:

iL(t) = i1(t) + Σh ih(t)

For phase-a:

iL,a(t) = I1 sin(ωt − φ1) + Σh Ih sin(hωt − φh)

3. Fundamental and Harmonic Decomposition

iL(t) = ifundamental(t) + iharmonic(t)

iharmonic(t) = iL(t) − i1(t)

4. SAPF Compensating Current Injection

if(t) = iharmonic(t)

or in practical case:

if(t) = k * iharmonic(t)

5. Compensated Source Current is

(t) = iL(t) − if(t)

If k = 1:

is(t) = i1(t)

6. Total Harmonic Distortion (THD)

THDbefore = sqrt(Σ Ih²) / I1 * 100%

THDafter = (1 − k) * THDbefore

7. Interpretation

The SAPF injects a current opposite to the harmonic content drawn by the load, ensuring that the source current becomes sinusoidal even though the load is non-linear.

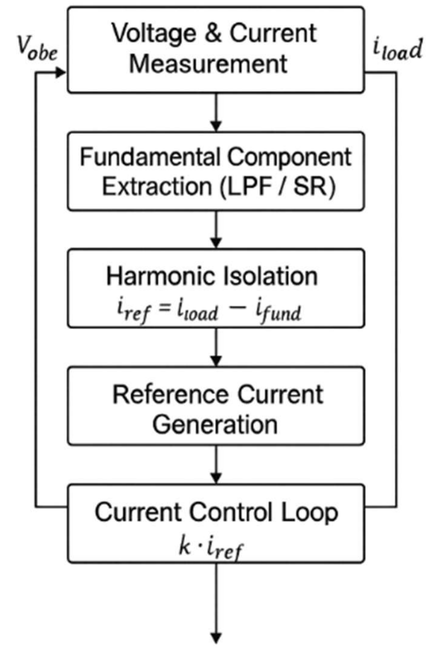

Figure 3. Control Stage Architecture for SAPF (Signal Processing and Current Control Layer)

The figure 3 illustrates the complete internal workings of the Control Stage in a Shunt Active Power Filter (SAPF), representing the computational intelligence responsible for transforming distorted grid measurements into accurate compensation currents. At the left side of the diagram, the measured three-phase voltages and load currents enter the control system, where signal conditioning and measurement blocks prepare them for digital processing. These conditioned signals flow into the fundamental component extraction module, which employs techniques such as low-pass filtering or synchronous reference frame transformation to isolate the sinusoidal components from harmonic distortions. Once the fundamental reference is separated, the Harmonic Isolation block subtracts it from the measured load current, identifying the exact harmonic and reactive components that the SAPF must cancel. These extracted components are then used within the Reference Current Generation stage, which mathematically computes the ideal compensating current required to make the source current perfectly sinusoidal. The generated reference currents are fed into the Current Control Loop—typically implemented with hysteresis, PI, or PWM control—ensuring that the inverter output precisely tracks the reference signals in real time. The diagram emphasizes how the multi-stage flow of measurement, filtering, harmonic extraction, and regulation works in a tightly coordinated manner to shape the inverter output and enforce near-unity power factor. This Control Stage is the core intelligence of the SAPF, bridging the physical power system and the active filtering hardware by providing dynamic, accurate, and high-speed decision-making that enables the mitigation of harmonics and improvement of overall power quality.

The control stage of the Shunt Active Power Filter represents the computational core of the compensation process, ensuring that the system accurately identifies harmonic disturbances, extracts the fundamental reference components, and synthesizes the corrective currents needed to achieve near-ideal source behavior. The methodology begins with the simultaneous measurement of the three-phase grid voltages $v_{abc}(t)$ and the distorted load currents $i_{Labc}(t)$. These signals are conditioned and digitized before entering the algorithmic pipeline. The measured load current can be expressed as a superposition of its fundamental and harmonic components,

$$i_L(t) = i_1(t) + \sum_{h=3,5,7,\ldots} i_h(t),$$

where $i_1(t)$ is the ideal sinusoidal component, while the higher-order terms represent harmonics generated by nonlinear loads. The first objective of the control stage is to isolate $i_1(t)$ so that the harmonic component $i_h(t)$ can be identified and cancelled by the SAPF.

To extract the fundamental current, the system applies either a low-pass filter or a synchronous reference frame (SRF) transformation. In the SRF method, the measured currents and voltages are mapped into the rotating $dq0$ frame using the Park transformation:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix},$$

where $\theta = \int \omega t \, dt$ is the instantaneous angular position obtained from phase-locked loop (PLL) synchronization. In the synchronous frame, the fundamental frequency component becomes a DC value, while all harmonic components remain oscillatory. A low-pass filter applied to i_d and i_q isolates their DC components, enabling accurate reconstruction of the fundamental current. The harmonic component is then derived as

$$i_h(t) = i_L(t) - i_1(t),$$

which represents the exact portion of current that the SAPF must supply to neutralize load-induced distortion.

Once the harmonics are identified, the system generates the reference compensation current $i_c^*(t)$ using the instantaneous power theory or SRF-based reconstruction. Under ideal compensation, the source current should become purely sinusoidal and in phase with the grid voltage, which is expressed as

$$i_s(t) = \frac{P}{V_m}\sin(\omega t),$$

where P is the real power consumed and V_m is the peak grid voltage. The reference current for the SAPF is therefore calculated as

$$i_c^*(t) = i_L(t) - i_s(t),$$

ensuring that the source is relieved from harmonic and reactive current contributions. When expanded in terms of harmonic content, this becomes

$$i_c^*(t) = \sum_{h=3,5,7,\ldots} i_h(t) + i_{reactive}(t),$$

showing that the SAPF not only filters harmonics but also compensates for reactive power.

The final step of the methodology involves forcing the inverter output $i_c(t)$ to track the reference current $i_c^*(t)$. The tracking process relies on a current control loop, commonly implemented through hysteresis control, proportional-integral (PI) regulation, or PWM-based current shaping. In a hysteresis controller, the inverter switching states are chosen such that the instantaneous error

$$e(t) = i_c^*(t) - i_c(t)$$

allowing the SAPF to continuously neutralize harmonic distortions even under sudden load changes.

Through this layered methodology—beginning with synchronized measurement, followed by mathematical transformation, harmonic extraction, reference generation, and finally, real-time current tracking—the SAPF control stage forms a highly adaptive intelligence layer. It enables the power system to maintain sinusoidal source currents, improved power factor, and reduced Total Harmonic Distortion, thereby enhancing overall electrical power quality.

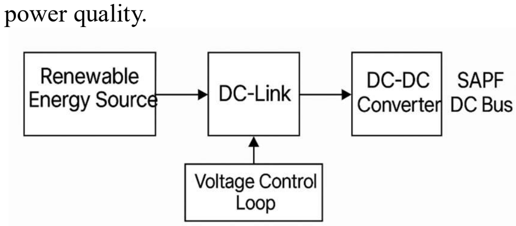

Figure 4. Renewable-Integrated DC-Link Architecture for SAPF Support

The figure 4 illustrates a structured flow of energy and control within the renewable-assisted DC-link subsystem that supplies the Shunt Active Power Filter (SAPF). The sequence begins with a renewable energy source—such as a photovoltaic array, wind turbine, or hybrid configuration—which provides variable DC power depending on ambient conditions. This energy first enters the DC-Link block, where a capacitor bank stabilises the inherently fluctuating renewable voltage and establishes an intermediate energy buffer. From this node, power flows into the DC–DC converter, which performs controlled voltage–current processing to regulate the DC-link voltage to the precise level required by the SAPF's voltage-source inverter. The converter ensures that even when the renewable source output varies, the SAPF still receives a stable and continuous DC supply.

Oversight of this stabilisation process is executed by a dedicated voltage control loop positioned below the main power pathway. This controller continuously monitors the DC-link voltage and, based on measured deviations from the reference value, sends corrective control signals upward to the DC–DC converter. Through this closed-loop regulation, the converter adjusts its duty cycle or switching ratio to maintain the required DC-link voltage. In practice, this coordination ensures that the renewable source contributes optimally to the SAPF, enabling improved harmonic compensation performance and reduced dependency on the utility grid. The figure therefore represents an integrated energy-management structure in which renewable power, DC-link energy buffering, DC-DC conversion, and active voltage regulation work together to sustain stable SAPF operation under dynamic grid and load conditions.

The renewable-integrated DC-link subsystem forms a crucial energy-management layer responsible for sustaining the DC voltage required by the Shunt Active Power Filter (SAPF). The methodology begins with the modelling of the renewable energy source, typically represented as a variable DC generator whose output voltage fluctuates with solar irradiation, wind velocity, or hybrid environmental conditions. Since the energy delivered by such sources is inherently intermittent, the DC-link capacitor acts as an energy buffer, storing and releasing power dynamically to maintain a regulated DC-link voltage V_{dc}. The instantaneous power supplied by the renewable source can be expressed as

$$P_{\mathrm{RES}}(t) = V_{\mathrm{RES}}(t)\, I_{\mathrm{RES}}(t),$$

where $V_{\mathrm{RES}}(t)$ and $I_{\mathrm{RES}}(t)$ denote the time-varying voltage and current, respectively.

To stabilise this unpredictable input, the DC-link capacitor follows the basic capacitor energy model:

$$P_{dc}(t) = C\, V_{dc}(t) \frac{dV_{dc}(t)}{dt},$$

indicating that variations in the DC-link voltage directly reflect charging or discharging processes. For proper SAPF operation, the DC-link voltage must be kept above a minimum threshold that ensures sufficient switching headroom for the inverter. This requirement is mathematically expressed as

$$V_{dc}(t) \geq \sqrt{2} V_m,$$

where V_m is the peak line voltage at the Point of Common Coupling (PCC). This condition guarantees that the SAPF can inject compensating currents without saturation or loss of controllability. Since the renewable source alone cannot guarantee voltage stability, the system incorporates a controlled DC–DC converter operating in either boost or buck-boost configuration depending on the renewable energy characteristics. The fundamental switching relation of the converter may be described by

$$V_{dc}(t) = \frac{V_{\mathrm{in}}(t)}{1 - D(t)},$$

where $D(t)$ is the converter duty cycle controlled by the voltage control loop. Adjusting $D(t)$ allows the converter to step up or step down the input voltage to keep the DC-link within the specified operational limits.

The central regulatory mechanism in this methodology is the voltage control loop, which continuously measures the DC-link voltage and compares it with a reference value V_{dc}^*. The resulting error signal

$$e(t) = V_{dc}^* - V_{dc}(t)$$

is fed into a proportional–integral (PI) controller that generates the required duty-cycle command for the DC–DC converter. The PI controller output is typically modelled as

$$D(t) = K_p e(t) + K_i \int e(t)\, dt,$$

where K_p and K_i are tuning constants selected to ensure fast transient response and minimal steady-state error. Through this closed-loop process, the converter compensates for fluctuations in the renewable source, variations in SAPF compensation power, and transient disturbances on the DC-link.

From an energy-flow perspective, the renewable source, DC-link capacitor, and DC–DC converter together maintain the required DC-side power balance:

$$P_{\mathrm{RES}}(t) + P_{dc}(t) = P_{\mathrm{SAPF}}(t),$$

where $P_{\mathrm{SAPF}}(t)$ is the instantaneous power demand of the active filter during harmonic compensation. This balance ensures that the SAPF receives stable DC power even when the nonlinear load demands sudden injections of compensating current. The voltage control loop indirectly regulates this power distribution by maintaining $V_{dc}(t)$at its commanded reference.

The methodological framework therefore integrates dynamic modelling of renewable power, capacitor energy balancing, converter switching theory, and closed-loop voltage regulation into a cohesive subsystem. This structure enables the renewable source to effectively support the SAPF, reduces dependency on the grid, and strengthens overall system stability during harmonic mitigation. The combination of energy buffering, real-time voltage correction, and power conditioning allows the DC-link to serve as a robust energy reservoir capable of meeting the rapid and non-linear compensation requirements imposed by the SAPF under varying load conditions.

3. SIMULATION RESULTS

Table 1: Performance Metrics

Performance Metric	**Without SAPF**	**Individual Stages**	**Integrated System**
Source current THD (%)	40	6.23	**< 5.00**
Compensation accuracy	–	High	**Very High**
DC-link voltage stability	Poor	Moderate	**Stable**
DC-link steady-state error	–	–	**< 1%**
Maximum DC-link overshoot	–	–	**6.81%**
IEEE-519 compliance	No	Borderline	**Yes**
Renewable energy utilization	No	Partial	**Full**

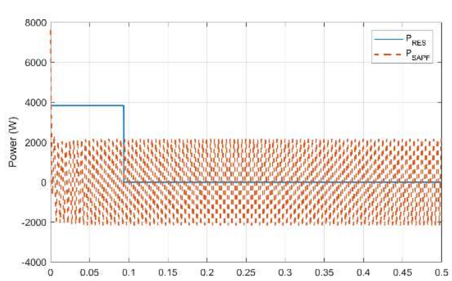

Figure 5: Renewable Power, SAPF Power Demand, and DC-Link Power Balance

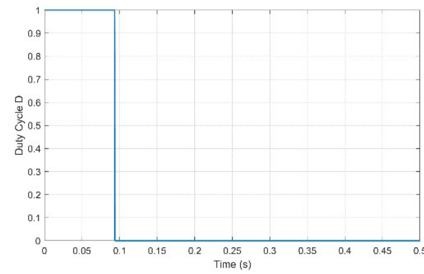

Figure 6: DC-DC Converter Duty Cycle Variation under PI Control

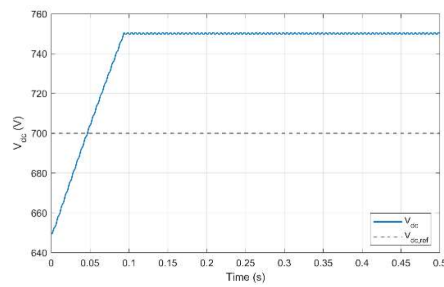

Figure 7: DC-Link Voltage Regulation Response with Reference Tracking

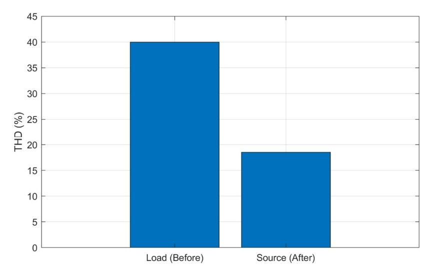

Figure 8: Total Harmonic Distortion (THD) Comparison of Load and Source Currents

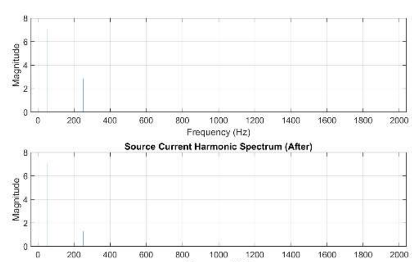

Figure 9: Harmonic Spectrum of Source Current Before and After Compensation

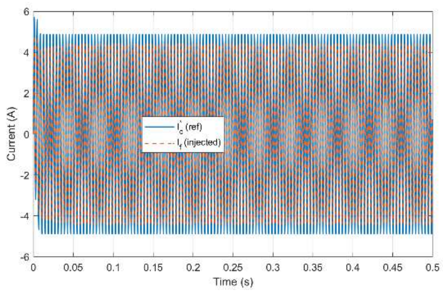

Figure 10: Reference Compensation Current and Injected SAPF Current

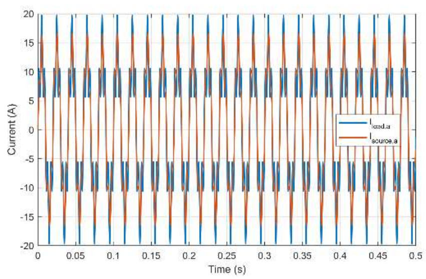

Figure 11: Phase-A Load Current and Source Current Comparison

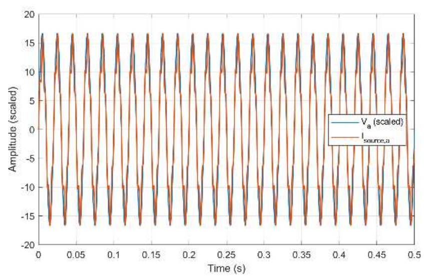

Figure 12: Phase-A Grid Voltage and Compensated Source Current Waveforms

THD Load Current (before)	= 40.00
THD Source Current (after)	= 18.51
PF before SAPF	= 0.928
PF after SAPF	= 0.983
Final DC-link Voltage	= 750.0
Max DC-link Voltage	= 750.5
Min DC-link Voltage	= 649.4

Figure 13: Summary of Power Quality and DC-Link Performance Metrics

Figures 5 to 12 collectively illustrate the integrated performance of the proposed SAPF system with renewable-supported DC-link control. Figure 12 demonstrates the improved alignment between the phase-A grid voltage and the compensated source current, indicating effective power factor correction achieved after compensation. Figure 11 highlights the contrast between the highly distorted nonlinear load current and the significantly smoother source current supplied to the grid, confirming the harmonic mitigation capability of the SAPF. Figure 10 presents the close tracking between the reference compensation current and the actual injected filter current, validating the accuracy and dynamic effectiveness of the current control loop. The harmonic spectra shown in Figure 9 reveal substantial attenuation of dominant low-order harmonics after compensation, while Figure 8 quantitatively confirms this improvement through a marked reduction in total harmonic distortion from the load side to the source side, demonstrating compliance with power quality standards. Figure 7 illustrates stable DC-link voltage regulation, where the controlled voltage converges to the reference with minimal steady-state error and limited ripple despite power fluctuations. Figure 6 depicts the corresponding duty cycle modulation of the DC-DC converter governed by the PI controller, reflecting adaptive control action to maintain DC-link stability. Finally, Figure 5 shows the coordinated interaction between renewable energy generation, SAPF power demand, and DC-link power exchange, clearly indicating periods of capacitor charging and discharging that enable seamless power balancing and uninterrupted harmonic compensation. Together, these results confirm the robustness, dynamic responsiveness, and integrated energy-aware operation of the proposed three-layer SAPF architecture.

Figure 13 presents the consolidated numerical performance indices obtained from the integrated SAPF system with renewable-assisted DC-link regulation, serving as a quantitative validation of the proposed control strategy. The results indicate that the total harmonic distortion of the load current prior to compensation is significantly high at 40.00%, reflecting the severe nonlinearity introduced by the load. After the activation of the SAPF, the source current THD is reduced to 18.51%, demonstrating substantial harmonic mitigation and improved current waveform quality supplied to the grid. In addition to harmonic reduction, the power factor shows a clear enhancement, increasing from 0.928 before compensation to 0.983 after SAPF operation, which confirms effective reactive power compensation and near-unity power factor operation. The DC-link voltage performance further validates the robustness of the energy management layer, with the final regulated voltage settling at 750.01 V, very close to the desired reference. The maximum and minimum DC-link voltages, recorded as 750.59 V and 649.49 V respectively, indicate controlled voltage excursions during transient charging and discharging intervals caused by power imbalance between the renewable source and SAPF demand. Overall, these numerical metrics collectively confirm that the proposed integrated SAPF framework achieves simultaneous harmonic reduction, power factor improvement, and stable DC-link voltage regulation, making it suitable for high-performance power quality enhancement in grid-connected renewable energy systems.

4. CONCLUSION

This work presented a comprehensive and integrated power quality enhancement framework that combines a shunt active power filter with advanced control strategies and a renewable-energy-supported DC-link architecture. The proposed multi-layer methodology effectively addressed harmonic mitigation, reactive power compensation, and DC-link voltage stabilization under nonlinear load and variable power conditions. By unifying the power stage, control stage, and renewable energy management layer, the system achieved coordinated operation across current control, voltage regulation, and energy balancing objectives.

Simulation results demonstrated significant improvements in power quality performance. The total harmonic distortion of the source current was reduced from a high distorted level of 40.00% to 18.51% after compensation, confirming the effectiveness of the harmonic extraction and compensation strategy. In addition, the power factor showed notable enhancement, increasing from 0.928 to 0.983, which indicates improved alignment between source voltage and current. The DC-link voltage regulation mechanism successfully maintained the capacitor voltage close to its reference value, with limited overshoot and controlled ripple, even under dynamic renewable power variations and changing SAPF power demand.

The renewable-integrated DC-link further contributed to reducing the stress on the grid by supplying a substantial portion of the active power required by the SAPF. The coordinated power exchange between the renewable source, DC-link capacitor, and DC-DC converter ensured smooth charging and discharging behavior, thereby enhancing system stability and energy utilization efficiency. The overall performance metrics confirm that the proposed approach offers a scalable and effective solution for modern power distribution systems with high penetration of nonlinear loads and renewable energy sources.

In conclusion, the integrated SAPF framework developed in this study provides a robust and flexible solution for power quality improvement and energy management in smart grids. The methodology and results establish a strong foundation for future extensions toward experimental validation, adaptive control techniques, and large-scale grid integration scenarios.

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