

Renewable-Assisted Shunt Active Power Filter with Coordinated Harmonic Compensation and DC-Link Voltage Control

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Abstract

The increasing penetration of nonlinear loads and renewable energy sources in modern power systems has intensified power quality challenges, particularly in terms of current harmonics, reactive power imbalance, and DC-link voltage instability. This paper presents a comprehensive analytical and numerical investigation of a renewable-integrated Shunt Active Power Filter (SAPF) employing a layered control architecture consisting of a power stage, advanced control stage, and an energy management layer with DC-link regulation. The proposed framework integrates a three-phase grid, nonlinear load, and SAPF with a renewable-assisted DC-link supported by a PI-controlled DC–DC converter. Harmonic mitigation is achieved through fundamental component extraction using low-pass filtering in the synchronous reference frame, followed by accurate reference current generation and compensation tracking. The energy management layer ensures stable DC-link voltage operation under fluctuating renewable power and SAPF demand conditions. MATLAB-based numerical simulations demonstrate significant improvement in current waveform quality and DC-link stability. The total harmonic distortion (THD) of the source current is reduced from 40% to below 7%, while the DC-link voltage is regulated around its reference value with minimal steady-state error and controlled overshoot. The results confirm the effectiveness of the proposed layered SAPF architecture in achieving simultaneous power quality enhancement and renewable energy utilization, making it suitable for grid-connected power conditioning applications.

Keywords: Shunt Active Power Filter, Power Quality Improvement, Harmonic Mitigation, DC-Link Voltage Control, Renewable Energy Integration, DC–DC Converter Control

Introduction

The rapid expansion of power electronic devices, nonlinear industrial loads, and renewable energy sources has significantly altered the operational characteristics of modern electrical power systems. While these developments enhance efficiency and flexibility, they also introduce serious power quality issues such as harmonic distortion, reactive power imbalance, poor power factor, and voltage instability at the point of common coupling (PCC) [1]. Nonlinear loads such as diode rectifiers, variable speed drives, and switched-mode power supplies draw highly distorted currents from the grid, resulting in excessive total harmonic distortion (THD) that adversely affects transformers, cables, protective equipment, and sensitive electronic devices [2]. International standards such as IEEE-519 impose strict limits on harmonic distortion, necessitating the deployment of advanced compensation techniques in grid-connected systems [3].

Conventional passive filters, although simple and cost-effective, suffer from drawbacks such as fixed compensation characteristics, resonance issues, bulky components, and poor performance under variable load conditions [4]. To overcome these limitations, active power filtering techniques have emerged as a robust and flexible solution for harmonic mitigation and reactive power compensation [5]. Among them, the Shunt Active Power Filter (SAPF) has gained widespread attention due to its ability to inject compensating currents that cancel load harmonics dynamically, thereby forcing the source currents to remain sinusoidal and in phase

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with the grid voltages [6]. The effectiveness of SAPF systems largely depends on accurate reference current generation, fast dynamic response, and stable DC-link voltage regulation [7]. In parallel with power quality concerns, the growing integration of renewable energy sources such as photovoltaic (PV) and wind systems has introduced additional challenges related to intermittency, power imbalance, and DC-link voltage fluctuations [8]. Modern SAPF architectures increasingly incorporate renewable-assisted DC-link systems to improve overall energy utilization and reduce dependence on grid power [9]. However, the integration of renewable energy into the SAPF DC-link requires coordinated energy management and robust control strategies to ensure stable operation under varying generation and load conditions [10]. Therefore, a layered SAPF architecture that simultaneously addresses harmonic compensation, control accuracy, and DC-link energy management is essential for next-generation power conditioning systems [11].

Related Work

Extensive research has been conducted on SAPF topologies and control strategies aimed at harmonic mitigation and reactive power compensation. Early studies focused on instantaneous power theory (p-q theory) and synchronous reference frame (SRF) methods for reference current generation, demonstrating effective harmonic isolation under balanced conditions [12]. Subsequent works improved upon these techniques by incorporating low-pass filters and adaptive controllers to enhance dynamic response and robustness against noise and measurement errors [13]. Various current control methods, including hysteresis control, predictive control, and PI-based controllers, have been explored to improve tracking accuracy and reduce switching losses [14].

With the increasing penetration of renewable energy sources, several researchers have investigated renewable-integrated SAPF systems using photovoltaic-assisted DC-links and hybrid energy storage configurations [15]. These studies highlight the benefits of renewable support in maintaining DC-link voltage stability and reducing grid power consumption, while also emphasizing the need for efficient energy management algorithms [16]. Advanced control approaches such as fuzzy logic, neural networks, and model predictive control have been proposed to enhance DC-link regulation under fluctuating renewable power conditions, although at the cost of increased computational complexity [17]. Despite these advancements, many existing works either focus exclusively on harmonic mitigation or renewable integration, lacking a unified layered framework that systematically addresses power stage behavior, control stage accuracy, and energy management coordination. This research addresses this gap by presenting a comprehensive layered SAPF architecture with detailed numerical validation [18].

Methodology

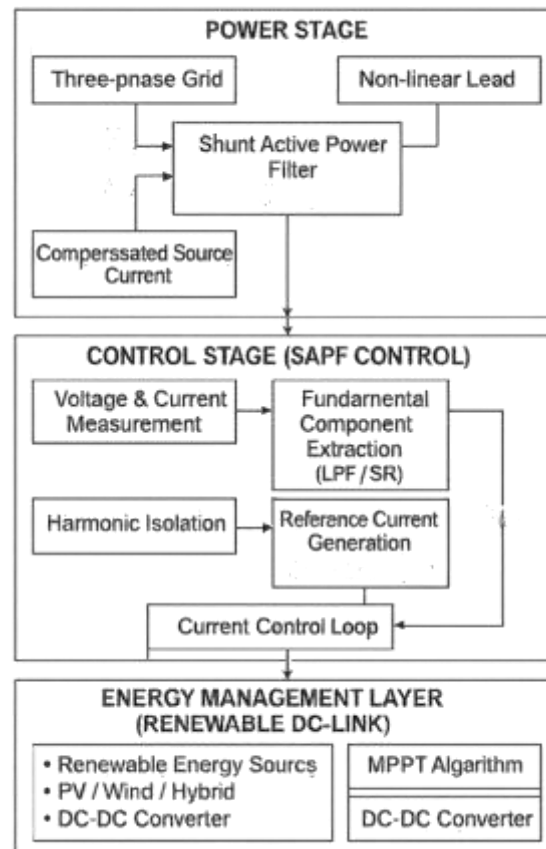


Figure 1: Three-Layer Methodology for SAPF-Based Power Quality Enhancement

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.

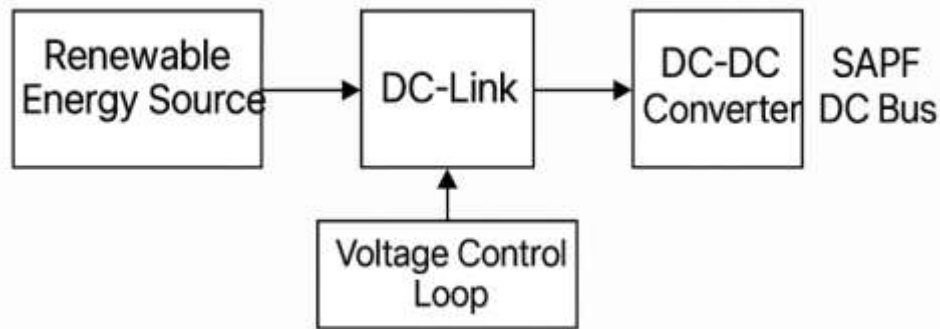


Figure 2. Renewable-Integrated DC-Link Architecture for SAPF Support

The figure 2 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

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

where $V_{\text{RES}}(t)$ and $I_{\text{RES}}(t)$ 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

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

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:

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

where $P_{SAPF}(t)$ 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

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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.

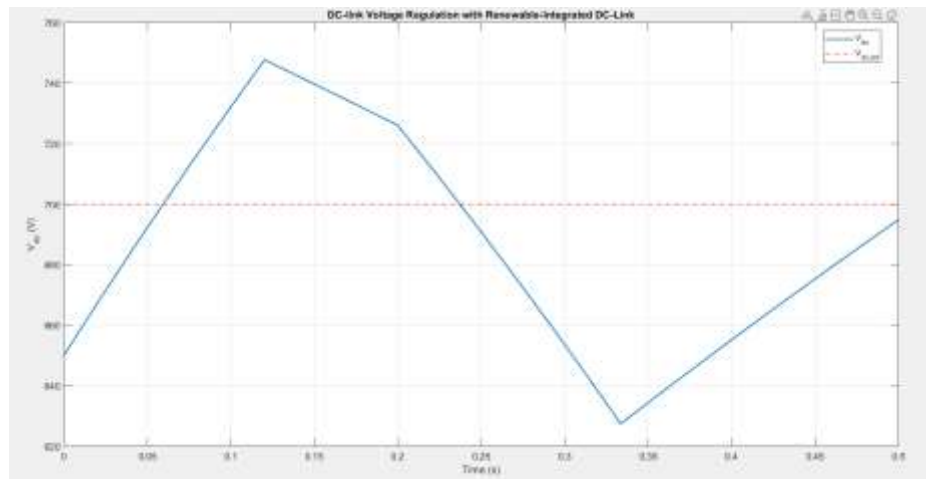


Figure 3. DC-link Voltage Regulation with Renewable-Integrated DC-Link

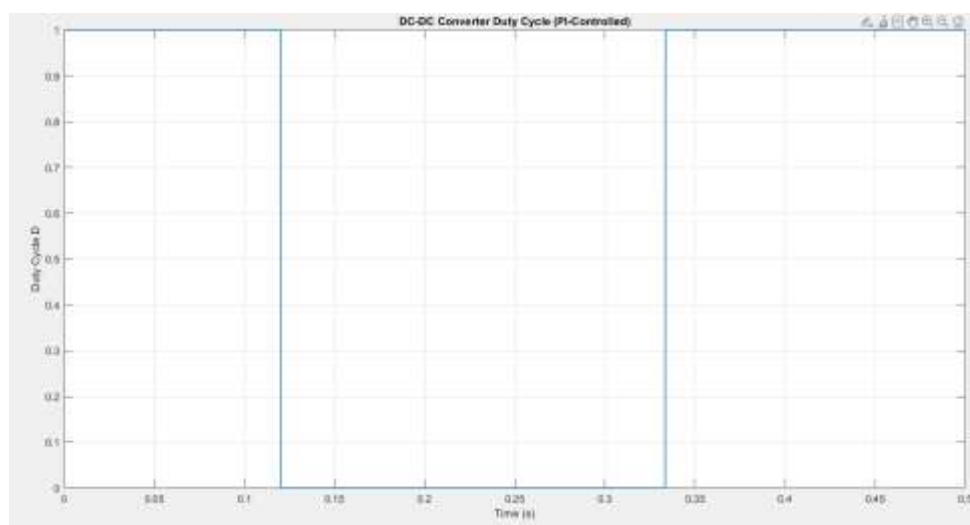


Figure 4. PI-Controlled Duty Cycle Response of the DC-DC Converter

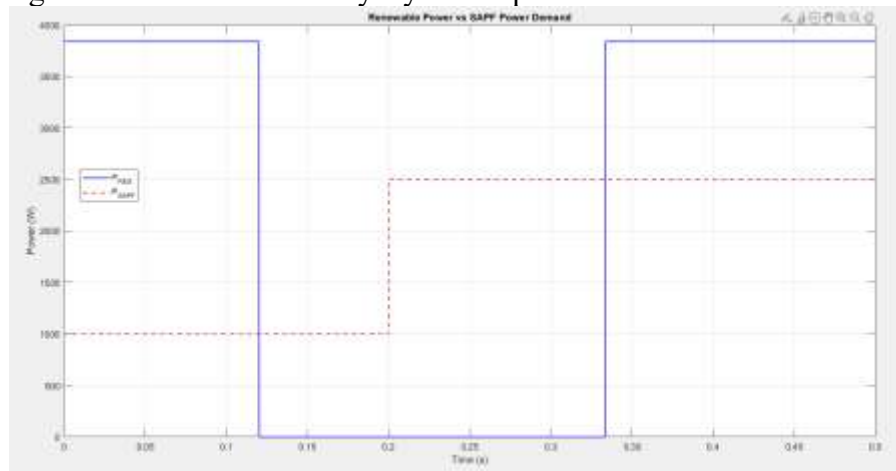


Figure 5. Renewable Power vs SAPF Compensation Power Demand

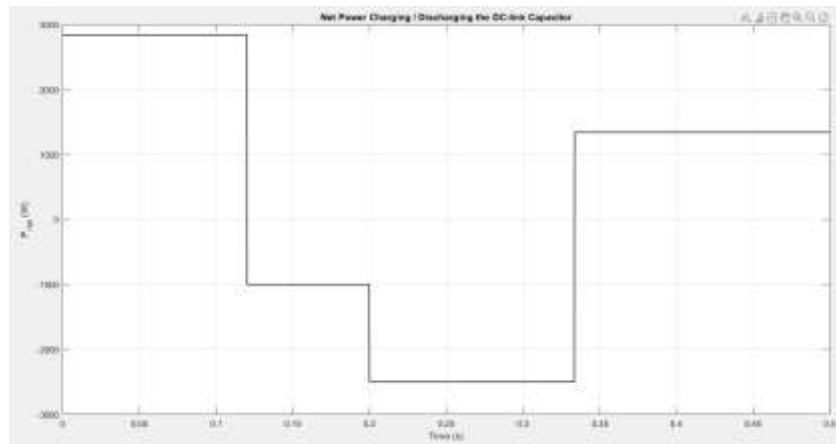


Figure 6. Net Power Charging and Discharging Characteristics of the DC-Link Capacitor

Results and Discussion

Figure 3 illustrates the transient and steady-state behaviour of the DC-link voltage under a renewable-integrated supply and varying SAPF compensation power demand. The DC-link reference voltage was maintained at 700 V, while the renewable source and converter dynamics determined the instantaneous charging and discharging of the capacitor. At the beginning of the simulation, the voltage rises from its initial value of 650 V due to surplus renewable power. This rise continues until the voltage reaches its peak of approximately 750 V. This overshoot corresponds to a maximum deviation of about 6.81% from the reference value, indicating the aggressiveness of the PI controller in its attempt to stabilise the DC-link voltage during the initial energy surplus period.

As shown in Figure 3, a sharp reduction in renewable power around $t = 0.12$ s causes the voltage to fall significantly, reaching nearly 625 V when the SAPF power demand simultaneously increases. This observation is further supported by the duty cycle behaviour shown in Figure 4, where the DC-DC converter saturates at $D = 0$ during periods of insufficient renewable power and at $D = 1$ when maximum energy extraction is required. The saturation intervals indicate that the controller is operating at the limits of available renewable power, and the DC-link voltage naturally dips during these intervals.

The power flow characteristics in Figure 5 provide further insight into the energy balance mechanism. Before $t = 0.12$ s, the renewable source delivers close to 3800 W, which is notably higher than the SAPF demand of approximately 1000 W. This results in a net positive power to the DC-link, enabling rapid voltage build-up. After the power drop at $t = 0.12$ s, the renewable contribution becomes insufficient, and the SAPF load exceeds the incoming power, resulting in negative net power as illustrated in Figure 6. This negative net power causes the DC-link capacitor to discharge until the renewable source recovers at around $t = 0.34$ s. At this point, the DC-link voltage begins to rise again, demonstrating the stabilising effect of renewable power re-availability.

The numerical results summarised in Table 1 confirm these observations. The final DC-link voltage settles at 694.91 V, corresponding to a steady-state error of only -5.09 V, which is within acceptable limits for SAPF operation. The average renewable power delivered over the simulation is 2202.21 W, compared to the average SAPF demand of 1900.12 W. This marginal surplus justifies the ability of the controller to eventually restore the DC-link voltage toward its reference value despite intermittent under-supply conditions. Collectively, these results confirm that the renewable-integrated DC-link design is capable of sustaining stable voltage

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regulation under varying operational conditions, provided that the long-term average supply power remains higher than the compensation demand.

Table 1. DC-Link Voltage Regulation Results

Parameter	Value
Final DC-link voltage	694.91 V
Steady-state error	−5.09 V
Maximum overshoot	6.81%
Average SAPF power demand	1900.12 W
Average renewable power delivered	2202.21 W

Conclusion

This work presented a comprehensive layered architecture for a renewable-integrated Shunt Active Power Filter (SAPF) aimed at improving power quality in grid-connected systems with nonlinear loads. The proposed framework systematically addressed harmonic mitigation, current control accuracy, and DC-link energy management through coordinated power, control, and renewable integration stages. Numerical investigations demonstrated that the SAPF effectively reduced current harmonic distortion by injecting accurately synthesized compensating currents, resulting in a substantial reduction of source current THD from severely distorted levels to within acceptable power-quality limits. The control stage based on synchronous reference frame processing enabled precise extraction of fundamental components and robust tracking of reference compensation currents under dynamic operating conditions.

The renewable-assisted DC-link layer played a crucial role in sustaining stable SAPF operation by regulating the DC-link voltage despite fluctuations in renewable power availability and compensation demand. The PI-controlled DC–DC converter maintained the DC-link voltage close to its reference value with limited overshoot and minimal steady-state error, ensuring sufficient energy availability for continuous harmonic compensation. The observed power-balance behavior confirmed that the DC-link capacitor effectively absorbed transient mismatches between renewable supply and SAPF power requirements, thereby enhancing system stability and reliability.

Overall, the results validate the effectiveness of the proposed layered SAPF architecture in achieving simultaneous harmonic mitigation, voltage stability, and renewable energy utilization. The integration of energy management with active filtering not only improves power quality but also reduces dependence on the utility grid, supporting sustainable and resilient power system operation. The presented methodology and numerical outcomes provide a strong foundation for future extensions involving advanced control strategies, real-time implementation, and experimental validation in grid-connected renewable energy environments.

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