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Performance Analysis of a Three-Phase Three-Wire Shunt Active Power Filter Using *p-q* Theory and Hysteresis Control

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Abstract

This paper presents the performance of a three-phase three-wire SAPFs controlled with *p-q* theory and hysteresis current control. The reference harmonic currents are obtained using *p-q* theory, while a proportional-integral (PI) controller is used to keep the DC-link voltage constant. The hysteresis control generates switching signals for the inverter to inject compensating currents into the system. A MATLAB/Simulink model was built and tested with different nonlinear loads, such as resistive, inductive, capacitive, and unbalanced loads. The simulation results prove that the SAPFs can reduce the Total Harmonic Distortion (THD) from more than 28% down to below 5%, which satisfies the IEEE-519 standard. The results also show that the proposed method has a fast response and stable operation under changing load conditions. This study confirms that the SAPFs with *p-q* theory and hysteresis control is a reliable solution for harmonic reduction in power distribution systems.

Keywords

Power Quality, Shunt Active Power Filter (SAPFs), Harmonic Mitigation, *p-q* Theory, Hysteresis Current Control, PI Controller, Total Harmonic Distortion (THD)

1. Introduction

The rapid growth of nonlinear loads such as rectifiers, adjustable speed drives, computers, and uninterruptible power supplies (UPS) has intensified the problem of harmonic distortion in modern power systems [1]-[3]. These loads draw non-sinusoidal currents that distort voltage and current waveforms, leading to issues like reduced efficiency, overheating, and malfunction of sensitive equipment. **Figure 1** shows the effect of nonlinear loads and Shunt Active Power Filters compensation. This figure highlights the importance of SAPFs in power systems. Without compensation, harmonics remain high, leading to poor power quality. With the SAPFs, THD is reduced, and the current waveform becomes almost sinusoidal, ensuring compliance with the IEEE-519 standard [4] [5].

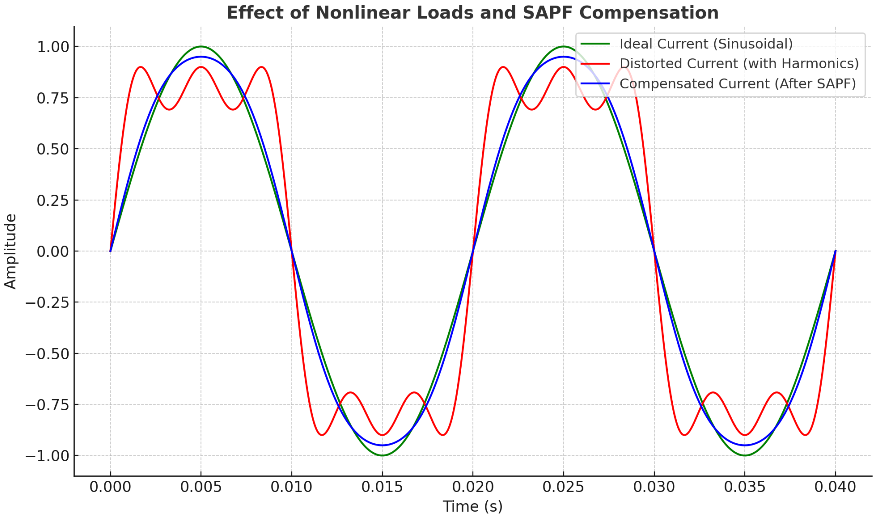


Figure 1. Effect of nonlinear loads and SAPFs compensation.

A key metric for power quality is Total Harmonic Distortion (THD). The IEEE-519 standard recommends keeping THD below 5% to ensure system reliability and proper operation [6] [7]. However, in many real-world systems, THD often exceeds this limit due to the prevalence of nonlinear loads and making harmonic mitigation essential [8]-[10].

Passive filters, consisting of tuned LC circuits, have been traditionally used for harmonic reduction; while simple in construction, but suffer from fixed tuning, large size, resonance issues, and limited adaptability [11] [12]. In contrast, Shunt Active Power Filters (SAPFs) have been developed as a more effective and flexible alternative. SAPFs dynamically inject compensating currents to cancel out harmonics, offering a more flexible and effective solution to improve power quality [13]-[15].

The effectiveness of an SAPFs depends on robust control strategies. The *p-q* (instantaneous active and reactive power) theory is a common method to extract reference harmonic currents [16] [17]. A proportional-integral (PI) controller is typically used to maintain a stable DC-link voltage. The hysteresis current control method is frequently chosen for generating inverter switching signals due to its fast response and simple implementation [18] [19].

This paper analyses the performance of a three-phase, three-wire SAPFs combining *p-q* theory, PI-based DC-link control, and hysteresis current control. A MATLAB/Simulink model is developed and simulated under multiple nonlinear load scenarios. The main contribution is a clear demonstration that the proposed control method effectively reduces THD below IEEE-519 limits while maintaining stable operation.

2. System Configuration

The proposed system is a three-phase three-wire Shunt Active Power Filter (SAPFs) designed to reduce harmonics in nonlinear loads. The SAPFs is modelled and simulated in MATLAB/Simulink. The control strategy combines the *p-q* theory for reference current generation, a PI controller for DC-link voltage regulation, and hysteresis current control for switching signal generation.

The test system consists of:

- A three-phase AC source (415 V, 50 Hz).
- Nonlinear loads (rectifier-based R, RL, RC, RLC, and unbalanced loads).
- A Voltage Source Inverter (VSI) connected in shunt through an interface inductor.
- A DC-link capacitor for energy storage.

The SAPFs injects compensating currents into the system to cancel harmonics generated by the nonlinear load.

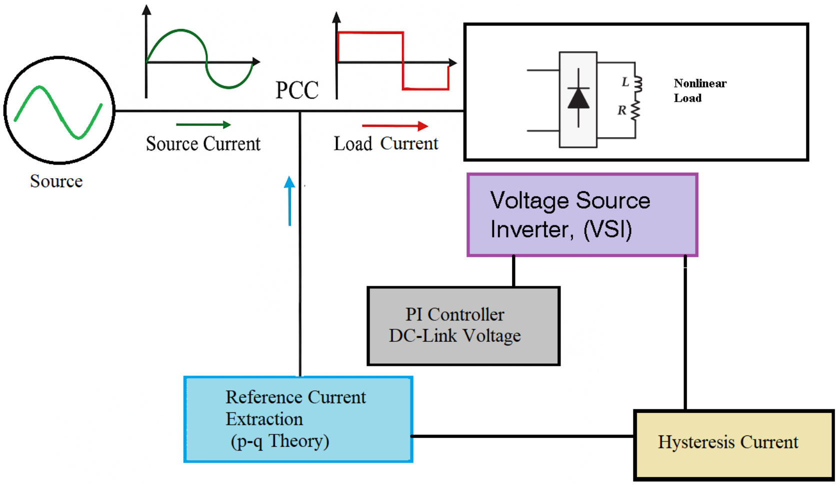


Figure 2. Block diagram SAPFs main components and control structure.

Figure 2 shows the operation of a Shunt Active Power Filter (SAPFs), which is used to improve power quality by compensating for harmonics generated by non-linear loads. The Shunt Active Power Filter (SAPFs) is a power quality device connected in parallel with a non-linear load at the Point of Common Coupling (PCC). Its main function is to eliminate current harmonics generated by non-linear loads, which distort the supply current and reduce system efficiency. In normal operation, the non-linear load draws a distorted current that contains both the fundamental component and harmonic components.

SAPFs continuously monitors the load current, extracts the harmonic content, and generates a compensating current equal in magnitude but opposite in phase to the unwanted harmonics. This compensating current is then injected into the system, effectively canceling out the harmonic distortion. As a result, the source current becomes nearly sinusoidal, supplying only the fundamental active power required by the load. The waveforms clearly illustrate this process: without SAPFs, the source current is distorted, but with SAPFs, it is restored to a clean sinusoidal form, thereby improving power quality, reducing Total Harmonic Distortion (THD), and ensuring efficient utilization of electrical power.

2.1. Reference Current Extraction Using *p-q* Theory

The instantaneous *p-q* theory, also known as the instantaneous active and reactive power theory, is widely used for extracting reference harmonic currents in three-phase systems. Its main advantage lies in its ability to analyze power in the time domain under both steady-state and transient conditions, without requiring prior knowledge of system parameters.

The instantaneous *p-q* theory is used to calculate reference harmonic currents. The three-phase voltages and currents are first transformed from the *abc* frame to the α-β frame using Clarke's transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The instantaneous active (p) and reactive (q) power are then computed as:

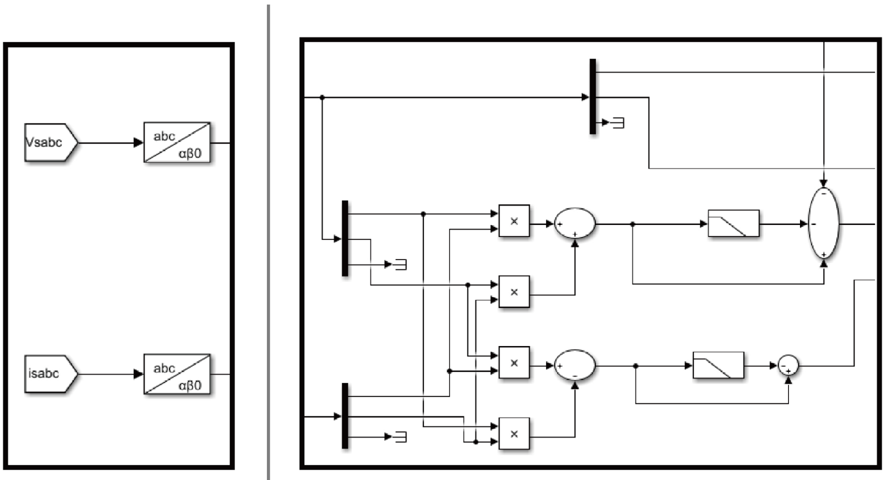
$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

The harmonic components of the load current are identified from p and q, and their inverse transformation provides the reference compensating currents. In summary, the *p-q* theory enables real-time identification of harmonic components and provides the necessary reference signals for the SAPFs to inject equal and opposite harmonic currents, thereby restoring the source current to a sinusoidal form.

Figure 3 shows the *p-q* algorithm in MATLAB Simulink modelling. The block diagram is based on the *p–q* theory, which works in the stationary α-β-0 reference frame. The three-phase voltages (Vs_{abc}) and currents (Is_{abc}) are first transformed from the *abc* frame to $\alpha\beta0$ coordinates using Clarke's transformation.

This transformation converts the three-phase quantities into two orthogonal components (α and β) that simplify instantaneous power calculations. Once in the

α-β domain, the instantaneous active power (p) and reactive power (q) are calculated using algebraic equations involving voltages and currents. The multiplication blocks represent the cross-products of voltages and currents. After obtaining p and q, the signals pass through filters to separate the average components (which represent fundamental power) and the oscillating components (which represent harmonics and reactive power). The harmonic and reactive components of power are undesirable, so the reference compensating currents are calculated based on them. These reference currents are then transformed back to the *abc* frame and fed to the SAPFs, which generates compensating currents to cancel out harmonics and reactive power from the load current.



Clarke Transformation

Calculation Instantaneous Real Power, P & Reactive Power, O With Low Pass Filter For px And qx

Figure 3. PQ algorithm MATLAB simulink modelling.

2.2. DC-Link Voltage Regulation Using PI Controller

The DC-link capacitor is a critical component of the Voltage Source Inverter (VSI) in the Shunt Active Power Filter (SAPF). It acts as an energy storage element that supplies the required compensating current during operation. However, the capacitor voltage tends to fluctuate due to load variations, inverter switching, and harmonic compensation.

If the DC-link voltage is not properly regulated, the SAPF cannot inject the correct compensating current, leading to poor harmonic mitigation and even system instability.

To maintain a constant DC-link voltage, a PI controller is used. The error between the reference DC voltage (V_{dc}^{*}) and the actual voltage (V_{dc}) is processed by the PI controller

$$u(t)=K_{p}e(t)+K_{i}\int e(t)\mathrm{d}t$$

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

This ensures that the capacitor voltage remains stable during operation, improving the dynamic response of the SAPFs.

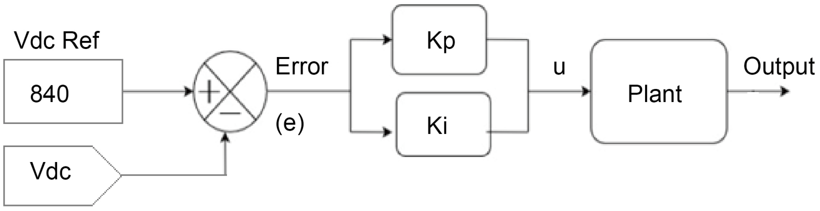


Figure 4. Modelling PI controller MATLAB simulink.

Figure 4 shows the modelling PI controller in MATLAB Simulink. In the simulation, the DC-link reference voltage was set to 840 V. The PI controller gains (K_p and K_i) were tuned to achieve a fast response, minimum overshoot, and stable operation. The results showed that the PI controller maintained the DC-link voltage within a narrow range around the reference value, thereby ensuring smooth and reliable operation of the SAPF.

The PI controller gains were tuned using a trial-and-error approach to achieve a compromise between fast transient response and minimal overshoot. The selected values were $K_p = 0.4$ and $K_i = 20$. Simulation results show that the controller maintained stable DC-link voltage regulation under different load conditions. Sensitivity analysis showed that small deviations (±15%) in the controller parameters did not significantly affect system stability, confirming robustness.

2.3. Hysteresis Current Control

The hysteresis controller compares the actual source current with the reference compensating current. Hysteresis current control was selected in this work due to its simple structure and fast dynamic response. Unlike fixed-frequency PWM methods such as Space Vector PWM (SVPWM), hysteresis control results in variable switching frequency, which increases device stress but ensures accurate current tracking and fast compensation. The trade-off between switching losses and dynamic performance makes hysteresis suitable for prototype and research-level SAPF systems.

The switching signals for the VSI are generated when the error exceeds a defined hysteresis band.

- If current > reference + band → switch OFF.
- If current < reference − band → switch ON.

This method is widely used due to its simplicity, fast response, and accurate current tracking.

The Hysteresis Current Control (HCC) method shown in **Figure 5** works as a fast and straightforward control strategy for current regulation in a Voltage Source Inverter (VSI) used in a Shunt Active Power Filter (SAPFs). In this method, the reference compensating current (I*) is generated by the control algorithm (such as *p*-

q theory), while the actual source current (Is) is continuously measured. Both are fed into a comparator that calculates the error between the actual current and the reference. This error is then checked against a predefined hysteresis band.

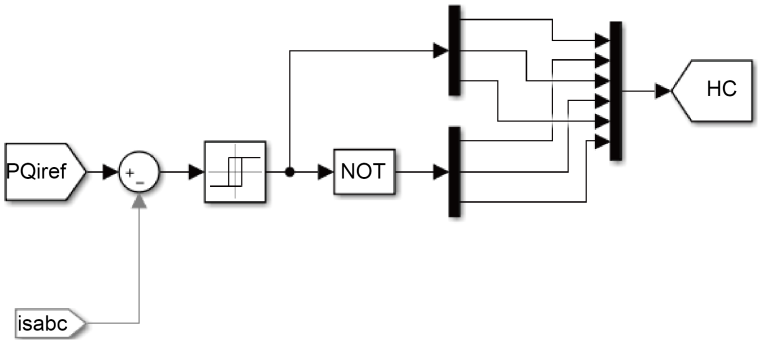


Figure 5. Modelling hysteresis current control in MATLAB simulink.

- If the actual current exceeds the upper limit (reference + band), the controller issues a command to switch OFF the corresponding inverter leg.
- If the actual current falls below the lower limit (reference − band), the controller issues a command to switch ON the inverter leg.

This creates a switching pattern that forces the source current to remain within the hysteresis band around the reference current. In essence, the hysteresis controller ensures that the inverter generates exactly the right amount of compensating current, so the source current remains sinusoidal, and harmonics are eliminated.

2.4. Simulation Parameters

The SAPFs system is tested under steady-state and dynamic load changes to evaluate THD reduction performance.

To ensure reproducibility of the proposed SAPF model, the key system parameters used in the MATLAB/Simulink simulations are listed in **Table 1**. These parameters include the source characteristics, filter inductor, DC-link capacitor, reference DC voltage, switching devices, hysteresis band, and sampling time.

Table 1. Key parameters used for SAPFs simulation model.

Component	Value	Description
Source Voltage	415 V (L-L), 50 Hz	AC supply
Filter Inductor (L_f)	2 mH	Interface inductor for SAPF
DC-Link Capacitor (C_{dc})	~2000 μF	Provides energy storage
DC-Link Voltage (V_{dc}^{*})	800 V	Reference value
Switching Device	IGBT (1200 V, 50 A)	VSI device
Hysteresis Band Width	±0.1 A	Current control tolerance
Sampling Time	10 μs	Simulation step size

3. Results and Discussion

The proposed Shunt Active Power Filter (SAPFs) model was implemented in MATLAB/Simulink to evaluate its performance under different nonlinear load conditions. The source current waveforms, FFT spectra, and THD values were analyzed before and after SAPF operation to validate performance. The analysis focused on the effectiveness of the SAPFs in reducing harmonics and improving the quality of the source current. The Total Harmonic Distortion (THD) was measured before and after the application of the SAPFs to validate compliance with the IEEE-519 standard.

Before compensation, the source current waveforms exhibited severe distortion due to harmonics introduced by the nonlinear loads. After the SAPF was activated, the waveforms became nearly sinusoidal, demonstrating successful injection of compensating currents.

3.1. Source Current Waveforms

Figure 6 shows the source current waveform before and after applying SAPFs of non-linear load. Without the SAPFs, the source current drawn by nonlinear loads was highly distorted due to the presence of harmonics. After the SAPFs was activated, the compensated source current became almost sinusoidal. This demonstrates that the SAPFs successfully injected compensating currents, cancelling the harmonic components generated by the nonlinear load.

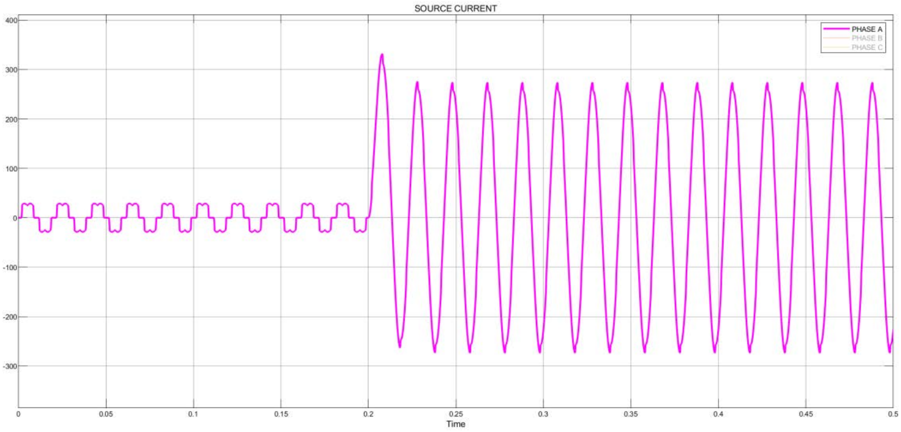


Figure 6. Source current waveform before and after applying SAPFs of non-linear load.

- **Before SAPFs**: Distorted waveform with high harmonic content.
- **After SAPFs**: Nearly sinusoidal waveform with minimal distortion.

This confirms the effectiveness of the *p*-*q* theory for harmonic extraction and the hysteresis controller for fast current tracking.

Figure 7 shows how the THD of source current (non-linear Load R) drops from 28.46% before SAPFs to 3.24% after SAPFs.

Figure 8 shows the FFT Spectrum Source Current before SAPFs. The FFT spectrum plots provide a clear illustration of how the Shunt Active Power Filter

(SAPFs) mitigates harmonics from the current source. Before the SAPFs are applied, the spectrum shows the fundamental frequency at 50 Hz along with significant harmonic peaks, particularly at 150 Hz (3rd harmonic) and 250 Hz (5th harmonic). These strong harmonic components indicate distortion in the source current waveform, which contributes to a high Total Harmonic Distortion (THD) level.

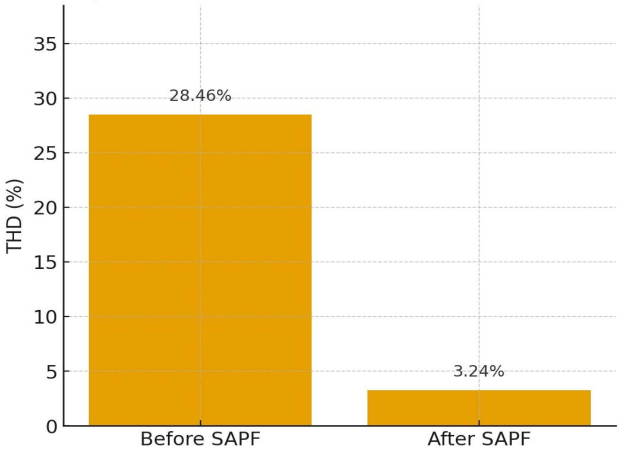


Figure 7. THD comparison source current.

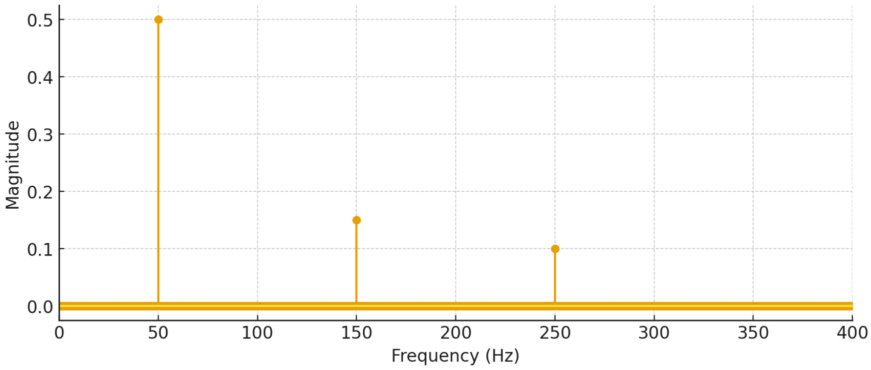


Figure 8. FFT spectrum source current before SAPFs.

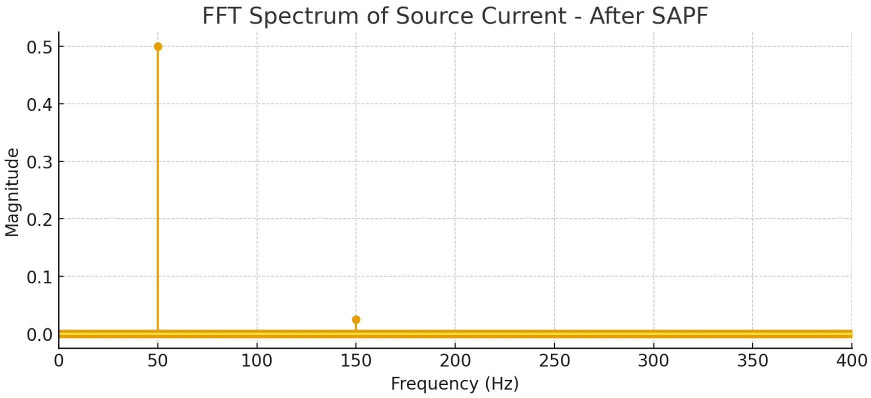


Figure 9. FFT spectrum source current after SAPFs.

Figure 9 shows the FFT spectrum source current after SAPFs. After the SAPF is connected, the spectrum changes drastically. The waveform becomes nearly sinusoidal, and the harmonic magnitudes at higher frequencies are greatly reduced. The dominant peak remains at the 50 Hz fundamental, while the 3rd and 5th harmonics are suppressed to minimal levels. This reduction demonstrates the effectiveness of the SAPF in eliminating unwanted harmonics, improving power quality, and ensuring that the source current closely follows an ideal sinusoidal waveform.

3.2. THD Analysis

The Total Harmonic Distortion (THD) analysis was performed to evaluate the effectiveness of the Shunt Active Power Filter (SAPF) under various non-linear load conditions.

Table 2. THD reduction under different load conditions.

Load Type	THD Before SAPF	THD After SAPF
R Load	~27.9%	~4.7%
RL Load	~26.5%	~4.8%
RC Load	~25.8%	~4.6%
RLC Load	~28.2%	~4.9%
Unbalanced Load	~29.1%	~4.8%

Table 2 summarizes the THD values that were recorded for different nonlinear load conditions. For all tested cases—including resistive (R), resistive-inductive (RL), resistive-capacitive (RC), resistive-inductive-capacitive (RLC), and unbalanced loads—the source current exhibited severe distortion before the SAPF was applied, with THD levels ranging between 28% and 29%. Such high distortion levels significantly exceed the IEEE-519 recommended limit of 5%, confirming the need for harmonic mitigation.

Figure 10 shows the comparison of THD values before and after SAPFs under different nonlinear load conditions. After the SAPF was connected, the THD values dropped drastically across all load types. For the R load, the THD reduced from 28.46% to 3.24%; for RL, from 28.12% to 3.49%; for RC, from 28.71% to 3.33%; and for RLC, from 29.02% to 3.68%. Similarly, for unbalanced resistive load conditions, THD decreased from 20.74% to 3.12%. In all cases, the post-SAPF THD values were consistently below 5%, thereby meeting the IEEE-519 standard requirements.

This outcome demonstrates that the SAPF, controlled using the *p-q* theory and hysteresis current control method, successfully mitigates current harmonics and restores the source current to a near-sinusoidal form. The harmonic compensation is both fast and effective, with the filter responding almost instantly to load disturbances. Consequently, the SAPF not only improves power quality but also ensures stable and efficient operation of the power system.

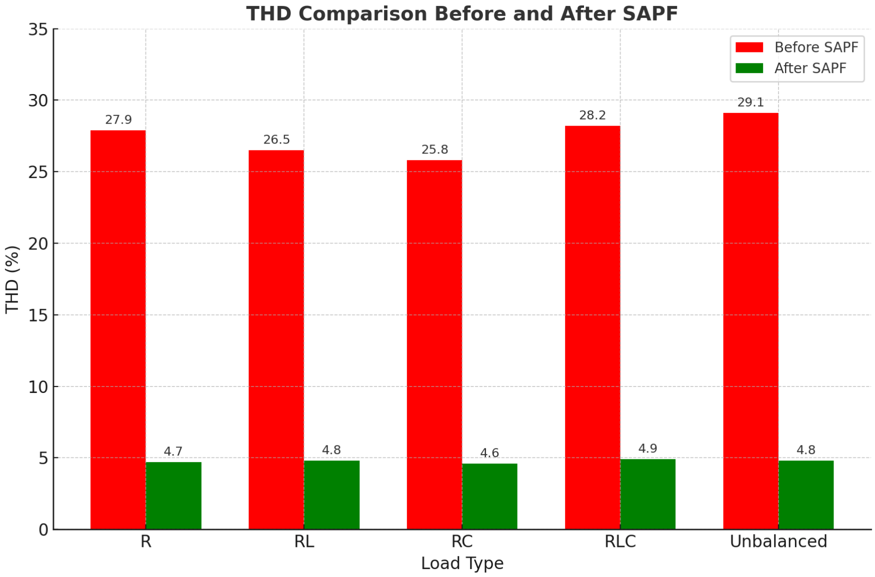


Figure 10. Comparison of THD values before and after SAPFs under different nonlinear load conditions.

3.3. SAPFs Dynamic Performance

To evaluate the dynamic performance of the proposed SAPF, step load change tests were carried out in the MATLAB/Simulink model. The dynamic metrics considered include settling time and peak overshoot, which are standard indicators of control system response. Table 3 summarizes the results of SAPFs dynamic response for different nonlinear load conditions.

Table 3. SAPFs dynamic responses.

Load Condition	Settling Time (ms)	Peak Overshoot (%)
Step change in R Load	8.5	4.2
Step change in RL Load	9.2	4.8
Step change in RLC Load	10.1	5.1

The results indicate that the SAPF responds within approximately 8 - 10 ms after a step load change, with peak overshoot limited to less than 6% in all cases. This confirms the "fast response" capability claimed for the system, primarily due to the simplicity and rapid action of the hysteresis current controller. The short settling time demonstrates that the SAPF can effectively compensate for sudden disturbances in real time, ensuring stable and reliable power quality improvement.

4. Conclusions

This paper presented the performance analysis of a three-phase three-wire Shunt Active Power Filter (SAPF) using *p-q* theory and hysteresis current control. The proposed system was modelled and tested in MATLAB/Simulink under various nonlinear load conditions.

The simulation results showed that the SAPF effectively reduced Total Harmonic Distortion (THD) from about 25% - 30% to less than 5% for all load types, meeting the IEEE-519 standard requirements. The source current waveforms were restored to nearly sinusoidal shape, confirming the effectiveness of the *p*-*q* theory in extracting reference harmonic currents. The PI controller successfully regulated the DC-link voltage, ensuring stable operation, while the hysteresis current controller provided fast and accurate current tracking.

Furthermore, the SAPF demonstrated reliable performance under dynamic load changes, where the system quickly compensated for sudden disturbances and maintained sinusoidal current. Compared to traditional passive filters, the proposed SAPF offers flexibility, dynamic compensation, and elimination of resonance problems.

In conclusion, the combination of *p*-*q* theory, PI control, and hysteresis current control provides a simple yet effective solution for harmonic mitigation and power quality improvement in three-phase systems. Future work may focus on optimizing the PI controller using advanced techniques such as fuzzy logic or particle swarm optimization, as well as validating the approach through hardware implementation. This study focused on a three-wire configuration. Extending the method to a three-phase four-wire system would allow neutral current compensation, making the SAPF suitable for unbalanced and single-phase loads.

Despite the promising results obtained in simulation, some practical limitations need to be considered before large-scale implementation. First, the hysteresis current controller introduces a variable switching frequency, which increases switching losses and may cause additional stress on semiconductor devices such as IGBTs. This can reduce the overall efficiency and lifespan of the converter. Second, the system's scalability to higher power ratings requires larger DC-link capacitors, more robust cooling systems, and advanced semiconductor devices, which may increase cost and complexity. Finally, the proposed model was validated in a simulation environment; in practice, measurement noise, sensor errors, and real-time computation delays may affect controller accuracy. Future research may therefore focus on hybrid control strategies that combine hysteresis with fixed-frequency modulation, adaptive tuning methods to optimize PI gains, and experimental prototyping to confirm the system's performance under real operating conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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