

Enhanced Active Power Filter Efficiency Using SRF-Based Control Strategy

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Abstract—This paper proposes an enhanced current control strategy for improving the performance of active power filters using Synchronous Reference Frame theory. The proposed technique enables the active power filters to provide precise harmonic compensation and effective reactive power mitigation, thereby improving overall power quality in grid-connected systems with nonlinear loads. Suppression of harmonic components in the line current remains a critical challenge in such systems. The synchronous reference frame based control strategy accurately detects and compensates for harmonic currents, ensuring balanced and nearly sinusoidal source currents with minimal total harmonic distortion. Furthermore, the approach facilitates efficient regulation of both active and reactive power while maintaining stable system operation. Simulation results demonstrate that the synchronous reference frame based active power filter significantly reduces total harmonic distortion, enhances dynamic response, and restores supply current quality, confirming the superiority of the proposed technique over conventional control strategies.

Keywords—Power Quality Filter, SRF-Based Control, Harmonic Mitigation, Reactive Power Control, THD.

I. INTRODUCTION

In recent years, the widespread integration of power electronic devices into electrical systems has exacerbated issues related to disturbances and harmonic distortions in power networks. Harmonics are primarily produced by nonlinear loads connected to the grid, which draw non-sinusoidal currents [1]. These current harmonics subsequently generate harmonic voltages at different points in the network [2]. Such harmonic pollution can lead to excessive heating of cables and electrical equipment, unexpected shutdowns of rotating machines, and, in severe cases, complete equipment failure [3].

To mitigate these disturbances and enhance the quality of electrical energy, various methods for power network compensation have been proposed in the literature. Traditional approaches, such as passive filtering, have been widely employed to address problems caused by harmonics and reactive power. However, these conventional systems exhibit several limitations, including susceptibility to resonance and limited flexibility under changing load conditions [4].

To address the limitations of conventional filtering techniques, modern solutions known as Active Power Filters (APFs) have been developed [5]. These devices improve

power quality by injecting compensating harmonic and reactive currents in opposition to the load currents, thereby ensuring that the grid delivers nearly pure sinusoidal currents in phase with the voltage. Among these solutions, parallel active filters, series active filters, and hybrid parallel-series filters commonly referred to as Unified Power Quality Conditioners (UPQCs) are the most widely implemented. Parallel active filters primarily compensate for harmonic and unbalanced currents as well as reactive power, whereas series active filters mitigate harmonic and unbalanced voltages and correct voltage sags. UPQCs offer a comprehensive approach, capable of addressing a broad range of power quality disturbances observed in electrical networks [6, 7, 8].

The APF serves two primary functions: (1) the identification of harmonic currents, and (2) the control of the inverter to inject compensating currents. This study focuses on the harmonic current identification methods [9], which is a critical stage in the filtering operation. Accurate estimation of harmonic currents is essential, as even a highly efficient inverter control system cannot provide effective compensation without precise reference signals. The overall performance of the APF particularly in reducing Total Harmonic Distortion (THD) [3, 10] of the source current and improving the power factor depends on both the accuracy of the reference current

identification and the implemented control strategy [11]. Various control methods have been proposed in the literature; despite differences in their underlying principles, they all aim to achieve a near-unity power factor and a source current waveform that closely resembles a pure sinusoid [12].

The primary objective of this research is to enhance the performance of the APF by minimizing residual distortions, providing effective reactive power compensation, and reducing the computational complexity of the control system. To accomplish these goals, the Synchronous Reference Frame (SRF) method is employed for the identification of reference currents, allowing harmonic detection and filtering to be performed directly in the current domain.

The APF control stage also considers the dynamics of the DC/AC inverter and its output filter to ensure accurate injection of compensating currents. For this purpose, a modulated hysteresis current control technique is implemented and optimized to satisfy the system's dynamic and operational requirements.

II. ANALYTICAL MODEL

The shunt active power filter (SAPF) consists primarily of a DC/AC inverter, a DC-link capacitor, and a coupling inductance. The energy storage element of the system is the capacitor C, which must maintain a nearly constant voltage level. Voltage fluctuations across this capacitor should remain minimal and must not exceed the maximum voltage rating of

the semiconductor devices. Conversely, for a given inductance value, the capacitor voltage must not fall below a certain threshold, as doing so would degrade the compensation performance of the active power filter.

The coupling inductance, which connects the SAPF to the power network, serves to filter high-frequency harmonic components in the current. These harmonics are generated by the voltage pulses produced by the inverter's switching action. The fundamental equations describing the behavior of the shunt active power filter and the electrical system are expressed as follows:

$$\begin{cases} v_a = v_{fa} + R_f i_{fa} + L_f \frac{di_{fa}}{dt} \\ v_b = v_{fb} + R_f i_{fb} + L_f \frac{di_{fb}}{dt} \\ v_c = v_{fc} + R_f i_{fc} + L_f \frac{di_{fc}}{dt} \end{cases} \quad (1)$$

Figure (1) shows a three-phase shunt active power filter compensating current harmonics of a nonlinear load.

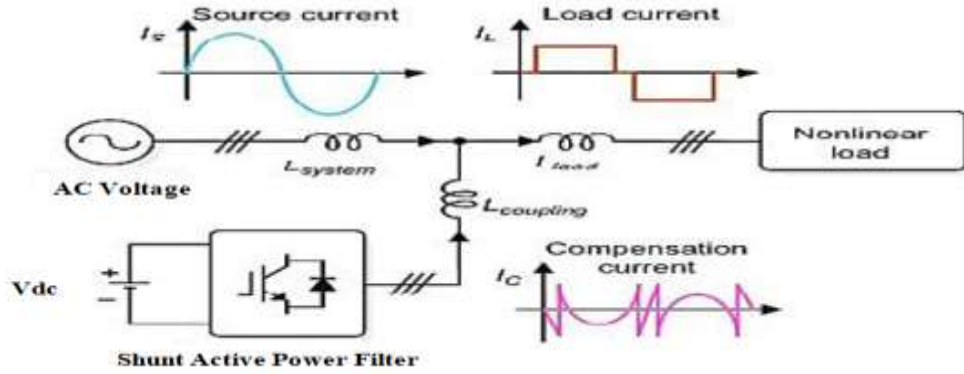


Fig. 1 Principle of shunt active power filter

III. SYNCHRONOUS REFERENCE FRAME THEORY

Various techniques classified under frequency domain, time domain, and time frequency analysis have been developed to detect and extract harmonic distortions in currents and voltages. Among these, the time domain SRF method [13, 14] is widely used for identifying reference harmonic currents. This approach offers notable advantages, including high accuracy, fast dynamic response, and ease of implementation, while effectively isolating unwanted harmonic components.

The first step in the SRF method is the transformation of three phase voltages and currents (a, b and c) into two-phase stationary components (α , β). This transformation simplifies the control process and facilitates harmonic identification. A Low-Pass Filter (LPF) is then employed to separate the fundamental components from the harmonic and DC components [15, 16].

In this method, the active power filter is controlled within the synchronous reference frame, where the load currents and supply voltages are expressed as follows:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & \frac{2}{\sqrt{3}} & \frac{3}{\sqrt{3}} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{3}{\sqrt{3}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} e_\alpha \\ e_\beta \\ e_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & \frac{2}{\sqrt{3}} & \frac{3}{\sqrt{3}} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{3}{\sqrt{3}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (3)$$

d, q current are:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \cdot \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (4)$$

The DC part resulted from the fundamental current and the AC part resulted from the harmonics using LPF [14]:

$$i_{Ld} = \bar{i}_{Ld} + \tilde{i}_{Ld} \quad (5)$$

$$i_{Lq} = \bar{i}_{Lq} + \tilde{i}_{Lq} \quad (6)$$

where, \bar{i}_{Ld} , \bar{i}_{Lq} : the DC mean value corresponds to the current from the source to the load due to the fundamental component and the \tilde{i}_{Ld} , \tilde{i}_{Lq} : AC value has no mean value and relates to the harmonic current from the source to the load. $\theta = \omega t$: is the angular frequency.

$$\begin{bmatrix} i_{AF\alpha}^* \\ i_{AF\beta}^* \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} \tilde{i}_{Ld} + i_c \\ \tilde{i}_{Lq} \end{bmatrix} \quad (7)$$

With a Park transformation as in the $p-q$ method, reference currents for the active filter are obtained:

$$\begin{bmatrix} i_{AFa}^* \\ i_{AFa}^* \\ i_{AFa}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{AF\alpha}^* \\ i_{AF\beta}^* \end{bmatrix} \quad (8)$$

The figure (2) Shows the bloc diagram of SRF method.

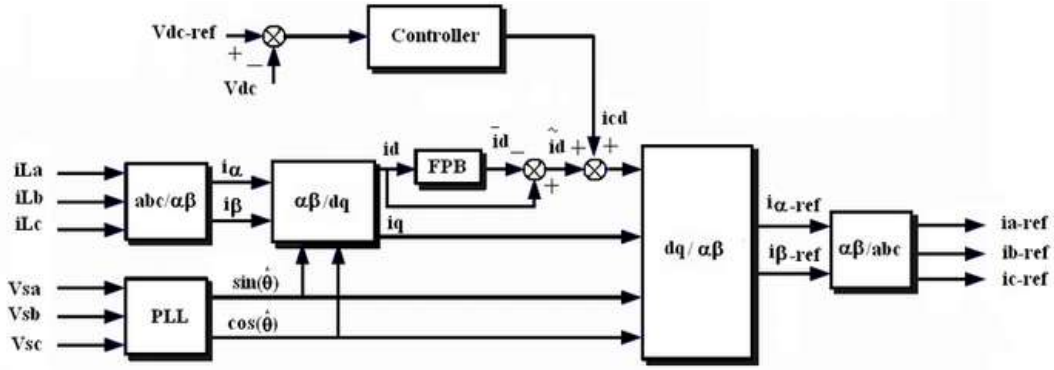


Fig.2. SRF method

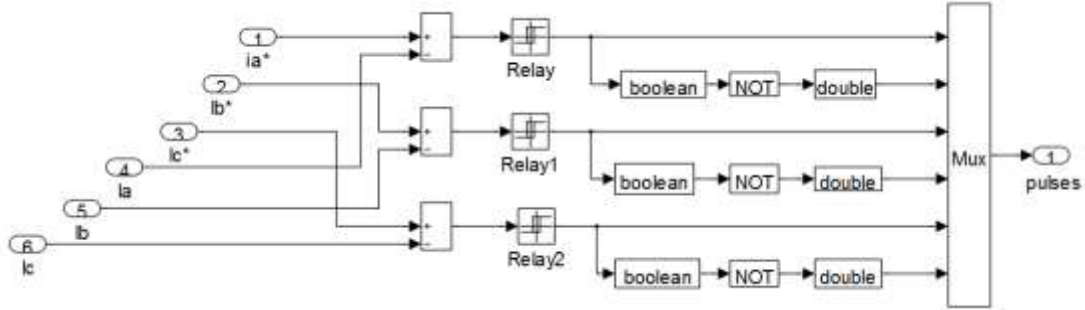


Fig. 3 Hysteresis band current control [13].

IV. HYSTERESIS BAND CURRENT TECHNIQUE

Hysteresis band current control does not require any knowledge of the system parameters, which is a significant advantage. However, it has the drawback of an uncontrolled switching frequency. The instantaneous error value can be calculated by subtracting the injected harmonic currents of the shunt active power filter from the identified reference harmonic currents, which are obtained using the Synchronous Reference Frame method (see Figure 2). This error is then fed into the hysteresis band current controller to generate gate pulses for the inverter power switches of the shunt active power filter [17, 18]. The hysteresis control law is illustrated in Figure (3).

The output of the hysteresis band current controller (S_{14}) consists of the switching pulses for the inverter power switches [19].

$$S_i = \begin{cases} 0 & \text{if } S_1 \text{ closed and } S_4 \text{ is open} \\ 1 & \text{if } S_4 \text{ closed and } S_1 \text{ is open} \end{cases} \quad (9)$$

V. PI CONTROLLER FOR DC BUS VOLTAGE

The advantage of controlling the DC source in an active shunt power filter is that the required supply power can be accurately transferred to the active power stage. The storage capacitor C absorbs power fluctuations caused by reactive power compensation. In a typical conditioner, the active power supplied by the source must equal the active power demanded by the load, plus a small amount of power to compensate for losses within the active filter [20]. Therefore, the DC voltage across the capacitor can be maintained at a constant level by comparing it with a reference value.

However, in non-ideal conditioners, the presence of harmonic currents due to load variations disrupts the actual

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power balance between the source and the load. In this scenario, most of the active power delivered is compensated by the inverter's DC capacitor. The deviation of the DC capacitor voltage from its reference value is optimally adjusted to maintain stability [21].

DC voltage control is implemented using a PI controller, where the inputs to the controller are the difference between the measured and its reference voltage [22, 23]. Figure 4 illustrates the internal structure of the control circuit. The error voltage is obtained by comparing the reference voltage with the measured voltage.

$$e(t) = V_{dc}^* - V_{dc} \quad (10)$$

The error signal is processed by a PI controller.

$$PI(s) = K_p + \frac{K_i}{s} \quad (11)$$

To obtain the reference harmonic currents, we use the following equation.

$$I_{Ld}^*(s) = \left(K_p + \frac{K_i}{s}\right) * (V_{dc}^* - V_{dc}) + \tilde{I}_{Ld}(s) \quad (12)$$

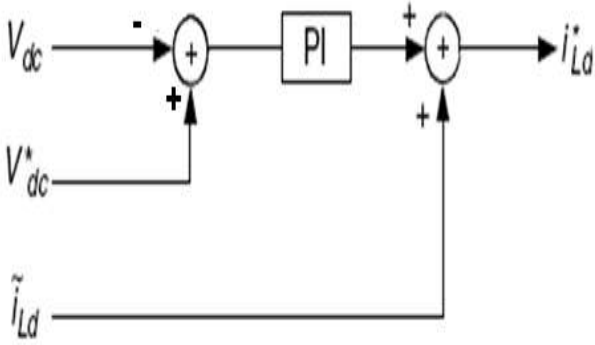


Fig. 4 DC voltage based on PI controller

VI. SIMULATION RESULTS

Simulation tests were conducted to verify the validity of the proposed system. The shunt active power filter was designed to compensate for harmonics caused by nonlinear

loads. The simulation results, obtained using hysteresis band current control and a PI controller, were examined through MATLAB/Simulink. The SRF method was employed to determine the three-phase reference harmonic currents, while the PI controller regulated the DC supply voltage of the shunt active power filter.

All harmonic spectrum analyses show that the harmonic levels are below the limits specified by the international standard IEEE 519 [3], in terms of Total Harmonic Distortion (THD). The system model parameters are summarized in Table 1.

TABLE 1 SYSTEM PARAMETERS

Input voltage	239.6 V ;
impedance source	0.01Ω ; 0.001e-3H
DC bus voltage	700V
Load	50Ω , 0.003 H
PI	K _p = 0.01
	K _i = 0.005

Figure (5) shows the waveforms of the input voltage. The three-phase supply voltages are imposed as balanced sinusoidal waveforms with a frequency of 50 Hz. These voltages are considered ideal, meaning that they are symmetrical and free from distortion or harmonics. This assumption ensures that any distortion observed in the current waveforms is mainly due to the nonlinear load rather than the supply source.

Figure (6) shows a zoomed view of the load line current waveforms before compensation. It can be observed that the currents are distorted and non-sinusoidal, indicating the presence of harmonic components generated by nonlinear loads.

The spectrum analysis of the load current, shown in Figure (7), indicates that the THD is 30.48%, which exceeds the limits imposed by the standards.

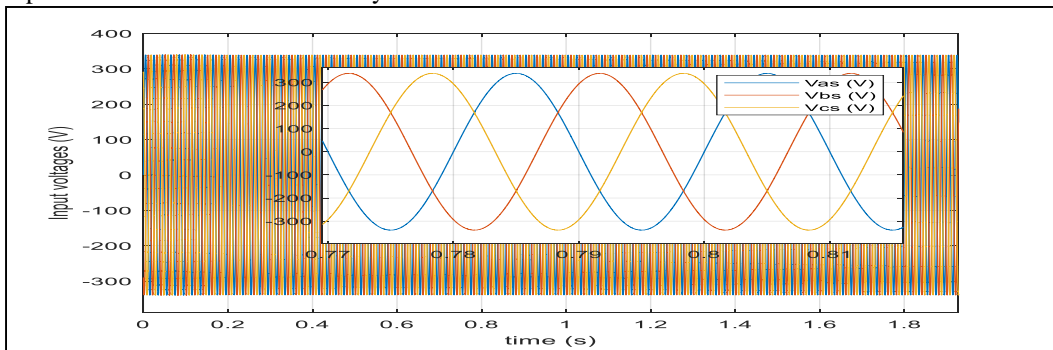


Fig. 5. Input voltage sources

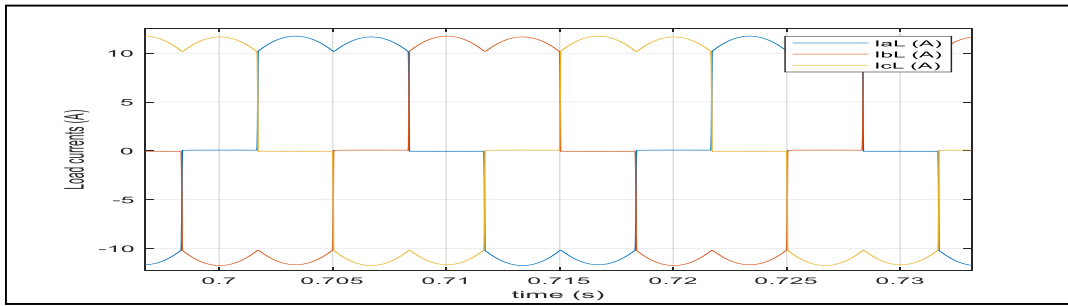


Fig. 6. Zoom of the load currents before compensation

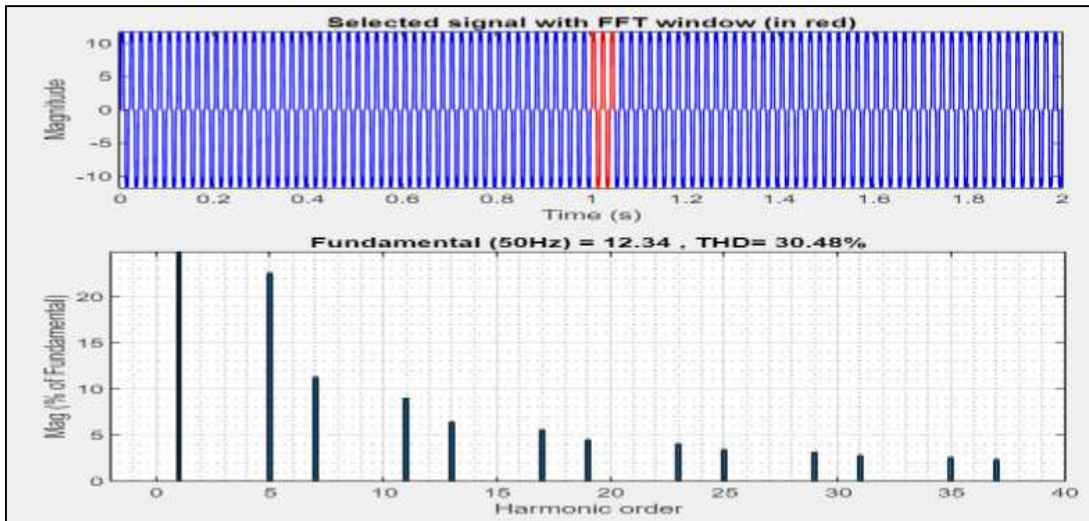


Fig. 7. Harmonic spectrum of the load currents before compensation

The harmonic currents identified using the SRF methods are shown zoom figure (8). These currents are injected into the grid in order to cancel the harmonics generated by the nonlinear load.

After compensation using SAPF, the three-phase source currents shown in the figure (9) becomes smooth, balanced, and nearly sinusoidal. The SAPF injects compensating

currents to cancel the harmonic components generated by the nonlinear load.

Figure (10) shows that the THD is significantly reduced, the source currents follow a fundamental sinusoidal waveform, and the overall power quality of the system is improved.

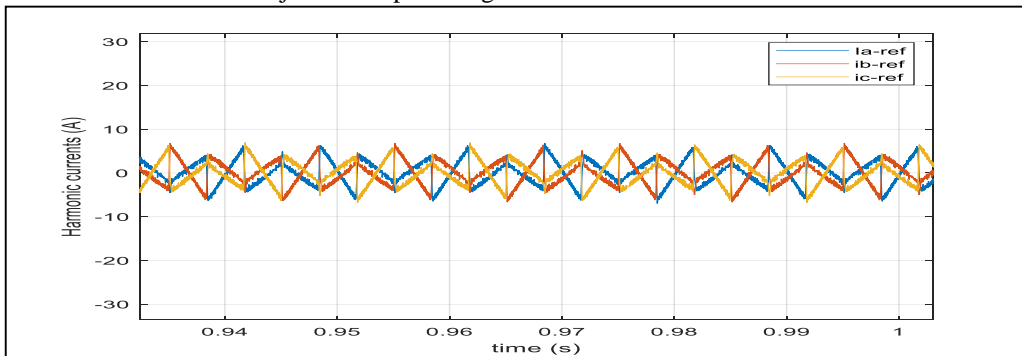


Fig. 8. Harmonics identified by the SRF method

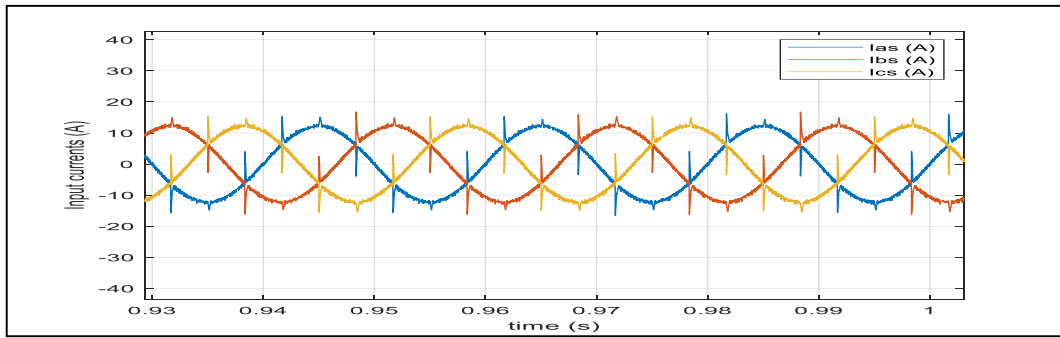


Fig. 9. Zoom of the load currents after compensation

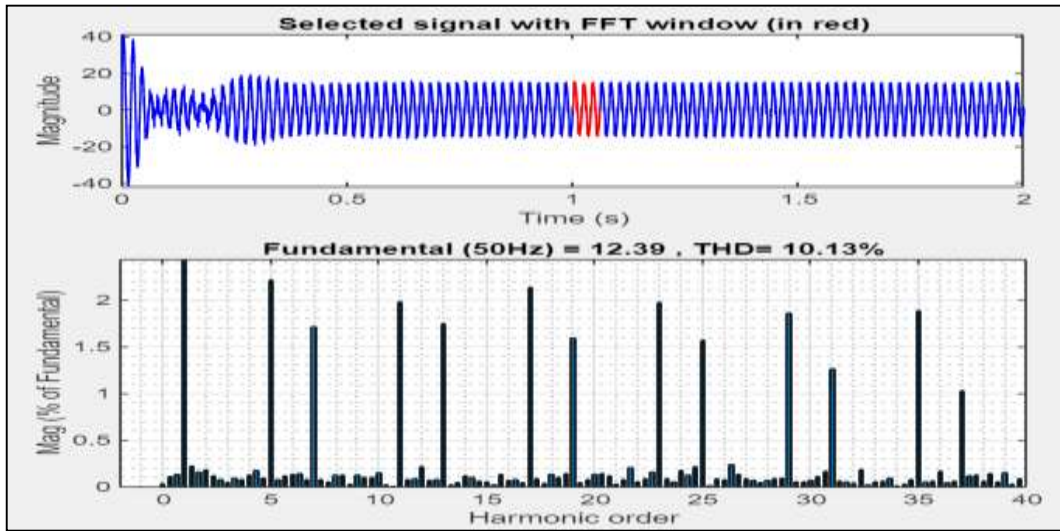


Fig. 10. Harmonic spectrum of the load currents after compensation

It shows that the spectrum analysis indicates the THD is 10.13%, which complies with the limits specified by the standards [3].

Figure (11) presents the comparison between the DC bus voltage and its reference value of 700 V. It can be observed that the voltage remains constant and perfectly follows its reference, thanks to the use of a PI controller.

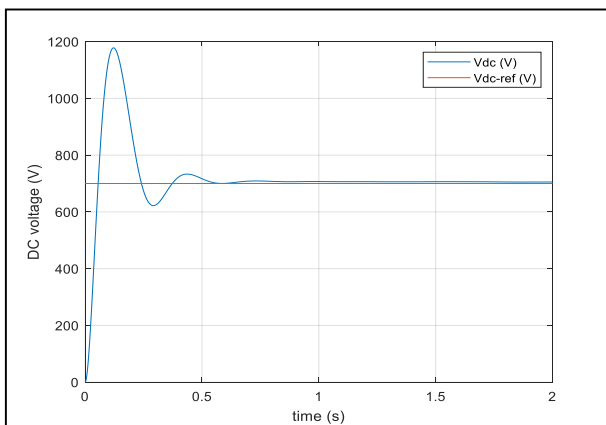


Fig. 11. DC bus voltage and its reference

Finally, in Figure 12, the active and reactive power consumption is shown. After compensation, it can be observed that the reactive power is close to zero, and only the active power consumption of approximately 4 kW remains.

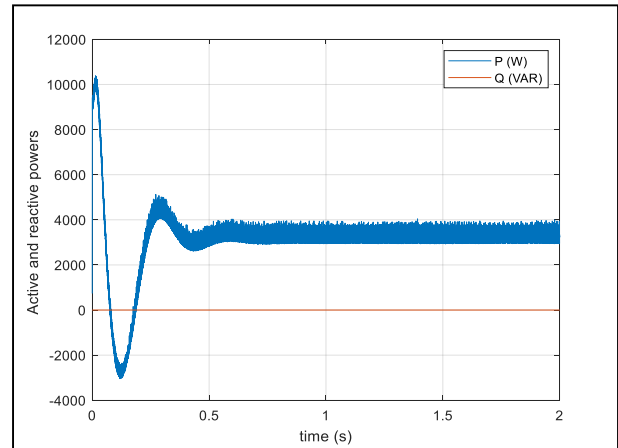


Fig. 12. Active and reactive powers after compensation

VII. CONCLUSION

This study demonstrates an effective approach for harmonic extraction and THD mitigation in power systems through the implementation of a SAPF based on the synchronous reference frame method. The incorporation of a PI controller ensures precise regulation of the DC-link voltage, enabling stable and efficient operation of the SAPF under varying load conditions. The proposed control strategy successfully generates nearly sinusoidal source currents and achieves substantial THD reduction, maintaining values well within internationally accepted standards. These results confirm that the designed SAPF system constitutes a reliable, efficient, and practical solution for harmonic mitigation and enhancement of power quality in modern electrical networks.

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