

Advanced Control Strategies for Harmonic Mitigation in Renewable Energy Systems using Shunt Active Power Filters

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ABSTRACT

This research proposes a compensation system designed to reduce reactive power and harmonic currents in a three-phase distribution network by integrating a photovoltaic (PV) system with a five-level inverter-based shunt active power filter (SAPF). The control strategy for the SAPF is based on the instantaneous power theory (p-q theory). The entire system, including the distribution network supplying a nonlinear load and the SAPF integrated with the solar system, is modeled and simulated using MATLAB/Simulink. The effectiveness of the proposed SAPF is evaluated using key performance metrics such as total harmonic distortion (THD) of the source current, power factor, and reactive power compensation. Extensive simulation results confirm the enhanced performance of the five-level inverter-based SAPF when combined with the PV system.

I. Introduction

The increasing use of power electronic devices, which often function as nonlinear loads, has led to significant power quality issues in distribution networks most notably the generation of harmonic currents and a decline in power factor. As utilities transition toward Smart Grid architectures, these power quality concerns become even more critical. In the context of the digital economy, maintaining high power quality within Smart Grid distribution systems is essential, as it directly impacts the reliability and efficiency of the grid, where both quality and cost-effectiveness are key requirements. Moreover, the integration of renewable energy sources such as solar, wind, and wave energy further intensifies these challenges due to their reliance on power electronic controllers, which inherently contribute to power quality disturbances [1]–[3].

Previous studies [4]–[7] have demonstrated the effectiveness of two-level voltage source inverter-based shunt active power filters (SAPFs) in compensating reactive power and mitigating harmonic currents in industrial power systems. As the control system plays a pivotal role in SAPF performance, it has been the focus of numerous recent investigations. Traditionally, proportional-integral (PI) controllers have been widely used in shunt active power line conditioners (APLCs) for regulating harmonic currents and maintaining DC-link voltage. However, in recent years, sliding mode controllers have gained considerable attention in power electronics and drive applications due

to their inherent robustness and adaptability [8], [9].

This research presents an innovative compensating system that integrates a solar system with a five-level inverter-based SAPF to mitigate reactive power and harmonic currents in three-phase distribution networks. The suggested SAPF makes use of a control method based on the p-q theory, which improves the system's capacity to handle problems with power quality. MATLAB/SIMULINK software is utilised to model and simulate the distribution network, which includes the five-level inverter-based SAPF and supplies nonlinear loads. With an emphasis on total harmonic distortion (THD) in the source current, power factor, and reactive power, the SAPF's performance is closely examined. The results of extensive simulations show that the integration of a solar system with a five-level inverter-based SAPF improves power quality more effectively.

II. Shunt Active Power Filter (SAPF) System

Shunt Active Power Filters (SAPFs) are advanced systems utilizing power electronic converters to enhance power quality by mitigating current and/or voltage harmonics generated by nonlinear loads. By preventing the propagation of harmonic distortions to sensitive equipment, SAPFs contribute significantly to the stability and reliability of the power distribution network (Fig. 1) [10], [11].

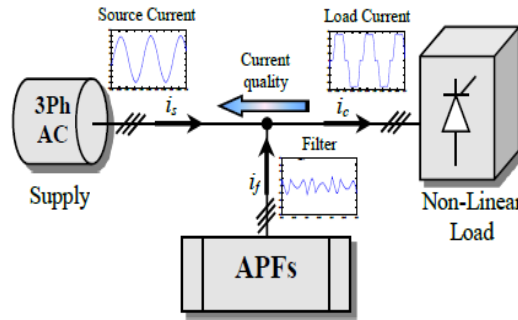


Figure 1. Schematic representation of the operating principle of the Shunt Active Power Filter.

Figure 2 presents the electrical configuration of a Shunt Active Power Filter (SAPF) integrated into a three-phase power system. The system is designed to perform power factor correction, load balancing, and current harmonic compensation. Instead of relying on an internal power source, the active filter is powered by a voltage-source inverter (VSI) equipped with a single DC-link capacitor, which is controlled to operate as a current source. The controller processes the measured phase voltages (v_a , v_b , v_c) and load currents (i_a , i_b , i_c) to compute the reference compensating currents (i_{fa}^* , i_{fb}^* , i_{fc}^*). These reference signals are then used by the inverter to generate the actual compensating currents (i_{fa} , i_{fb} , i_{fc}), effectively mitigating harmonic distortions and unbalances in the system.

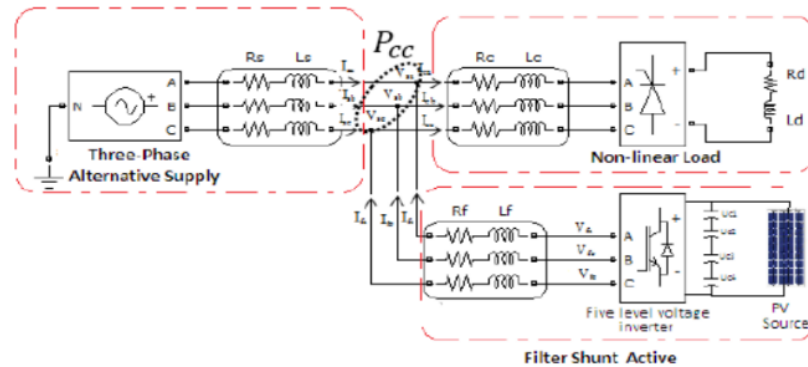


Figure 2. Equivalent circuit diagram of the Shunt Active Power Filter (SAPF)

Figure 3 illustrates the block diagram of a Shunt Active Power Filter (SAPF) integrated with a photovoltaic

(PV) power source, with its operation governed by a sliding mode control strategy. This control methodology is known for its robustness against system uncertainties and external disturbances, making it highly suitable for power quality applications. The integration of the photovoltaic source not only ensures a sustainable energy supply for the SAPF but also enhances the overall efficiency of the system. The sliding mode controller, by accurately tracking reference currents, enables the SAPF to effectively mitigate harmonic distortion, correct the power factor, and achieve load balancing within the distribution network [12], [13].

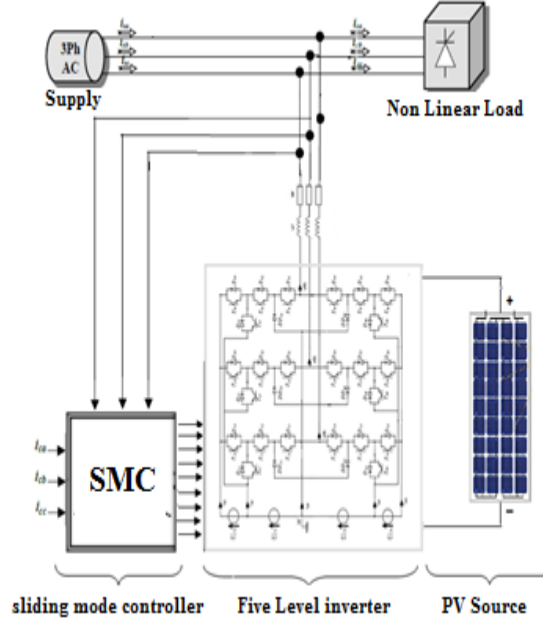


Figure 3. A block diagram showing the sliding mode control and solar energy source-powered Shunt Active Power Filter.

This advanced setup demonstrates how power quality challenges in modern electrical networks can be effectively mitigated through the integration of advanced control strategies and renewable energy sources.

III. Application of Sliding Mode Control in Shunt Active Power Filtering Systems

Sliding Mode Control (SMC) is a robust control technique designed to drive the system's state trajectory onto a predefined sliding surface and maintain its motion along this surface, ensuring a specific dynamic behavior towards equilibrium. Stability and performance requirements are routinely taken into account during the design of a sliding mode controller. Three crucial processes are involved in implementing SMC: determining the convergence condition, determining the control input, and choosing the sliding surface [14], [15].

Beyond selecting a surface from various alternatives, it is essential to evaluate the shape of each surface according to the specific objectives and details of the application. To ensure the convergence of a system variable to its desired value, [16] proposed the following general expression for defining the sliding surface:

$$S(X) = \left(\frac{\partial}{\partial t} + \lambda \right)^{r-1} e(X) \quad (1)$$

Where:

- $e(x) = X_{ref} - X$ is the deviation of the controlled variable from its reference,
- λ is a positive constant that influences the desired control bandwidth,
- r is the relative degree, representing the number of derivatives required to express the control law,
- $S(X) = 0$ results in a linear differential equation, for which $e(x) = 0$ is the only possible solution.

The convergence condition ensures that the system dynamics reach and remain on the sliding surface. A widely

adopted approach requires that the following inequality be satisfied:

$$S(X) \cdot \dot{S}(X) < 0 \quad (2)$$

The control input $U(t)$ is calculated to bring the controlled variable onto the sliding surface and then guide it toward the equilibrium point while maintaining the sliding mode condition. The control law is defined as:

$$U(t) = U_{eq} + U_n \quad (3)$$

where:

- U_{eq} is the equivalent control, assuming $\dot{S}(X) = 0$ during the sliding mode, representing the averaged control action,
- U_n is represents the corrective control action that ensures the system's trajectory is drawn toward the sliding surface while satisfying the convergence condition.

A simple relay function can be used for U_n :

$$U_n = k \cdot \text{sign}(S(X)) \quad \text{with } k > 0 \quad (4)$$

However, a high gain value k may induce chattering, which can be mitigated by replacing the discontinuous relay function with a smooth, continuous approximation:

$$U_n = k \cdot \frac{S(X)}{|S(X)| + \epsilon} \quad (5)$$

where ϵ is a parameter that controls the attenuation of oscillations.

Applying SMC to the control of the active power filter (APF) involves the following steps. From the dynamic equations governing the APF:

$$R_f I_{fK} + L_f \frac{dI_{fK}}{dt} = N_{gK} U_c - V_K \quad (6)$$

Where the active filter's output current is the variable under control. The chosen sliding surface is:

$$S = I_{fref} - I_f \quad (7)$$

Taking the derivative of the sliding surface:

$$\dot{S} = \frac{dI_{fref}}{dt} - \dot{I}_f \quad (8)$$

During the convergence phase, the condition $S(X) \cdot \dot{S}(X) < 0$ must hold. To reduce chattering, a continuous function is chosen for the attractive control:

$$U_n = -k \frac{S}{|S| + \epsilon} \quad (9)$$

From these equations, and considering the sliding mode condition $\dot{S}(X) = 0$, the control law is derived as:

$$N_{gK} = \frac{1}{U_c} \left(R_f I_{fK} + L_f \frac{dI_{fref}}{dt} + V_K + L_f K \frac{S}{|S| + \epsilon} \right) \quad (10)$$

This formulation provides a systematic approach to designing a sliding mode controller that ensures robust and stable performance in shunt active power filters, particularly in the presence of disturbances and system uncertainties.

IV. PV Model

Understanding the fundamental structure of a solar cell a thin semiconductor wafer with an embedded p-n junction is essential to the photovoltaic (PV) concept. The photovoltaic effect enables the direct conversion of solar energy into electrical power, occurring when sunlight's electromagnetic radiation excites the semiconductor material. When photons with energy exceeding the band-gap of the semiconductor strike the material, they generate electron-hole pairs, depending on the level of incident irradiation.

Accurately modeling a solar generator requires determining its equivalent electrical circuit. Since semiconductor junctions are the core components of PV modules, several mathematical models have been developed to represent the highly nonlinear behavior of these junctions. These models account for various factors that influence the output voltage and current of the PV generator. In this study, we adopt the widely used single-diode model (Figure 4), which incorporates both series and shunt resistances intrinsic to the PV cell [16], [17].

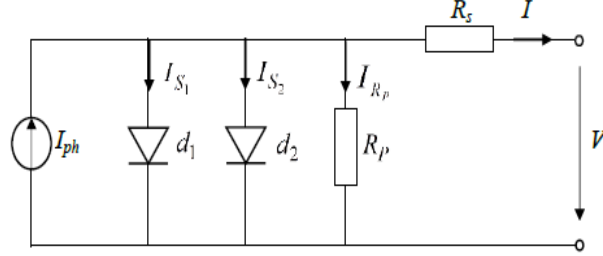


Figure 4. A photovoltaic cell model

In the equivalent circuit, the photocurrent generated by the solar cell is modeled as a current source I_{ph} , while the series and shunt resistances are represented by R_p and R_s , respectively. Typically, R_p has a high value and R_s a low one, allowing them to be neglected in simplified analyses. However, for accurate and detailed modeling, these resistances must be taken into account. Individual PV cells are interconnected to form PV modules, which are further combined in series-parallel configurations to construct PV arrays [18]–[20].

The mathematical model of the photovoltaic panel is expressed through equations (11) to (14), which serve as the foundation for deriving the equivalent electrical circuit. This circuit is essential for accurate simulation and performance evaluation of PV systems.

Equations:

$$I = I_{ph} - I_{S1} \left[e^{\frac{q(V+IR_s)}{kT}} - 1 \right] - I_{S1} \left[e^{\frac{q(V+IR_s)}{AkT}} - 1 \right] - \frac{V+IR_s}{R_p} \quad (11)$$

$$I = I_{ph} - I_{S1} \left[e^{\frac{q(V+IR_s)}{kT}} - 1 \right] - \frac{V+IR_s}{R_p} \quad (12)$$

$$I_{ph} = I_{sc} \quad (13)$$

$$I_s = \frac{I_{ph}}{\left(\exp\left(\frac{V_{oc}}{0.25sec}\right) - 1 \right)} \quad (14)$$

The photovoltaic system in this study includes the following components:

- Nine photovoltaic modules, each rated at 60 watts with an irradiation of 1000 W/m².
- A PV array operating at Maximum Power Point (MPP) with a power output of $P_{PV} = 9 \times 60 = 540$ W.
- A Maximum Power Point Tracking (MPPT) controller.
- A Boost converter (DC/DC) to step up the DC input voltage.

This configuration ensures efficient energy conversion and management within the PV system.

V. Simulation Results

V.1. Photovoltaic (PV) power system

Figure 5 depicts the output voltage generated by the photovoltaic (PV) array, which is then fed into the DC/DC converter. The measured output voltage of the PV array is $V_{PV} = 193.5$ V. This voltage level is essential for the efficient operation of the DC/DC converter, as it ensures that the system operates optimally and that the PV modules function near their Maximum Power Point (MPP). The recorded voltage value also demonstrates the effectiveness of the MPPT (Maximum Power Point Tracking) controller in maximizing the array's performance under the prevailing irradiation conditions.

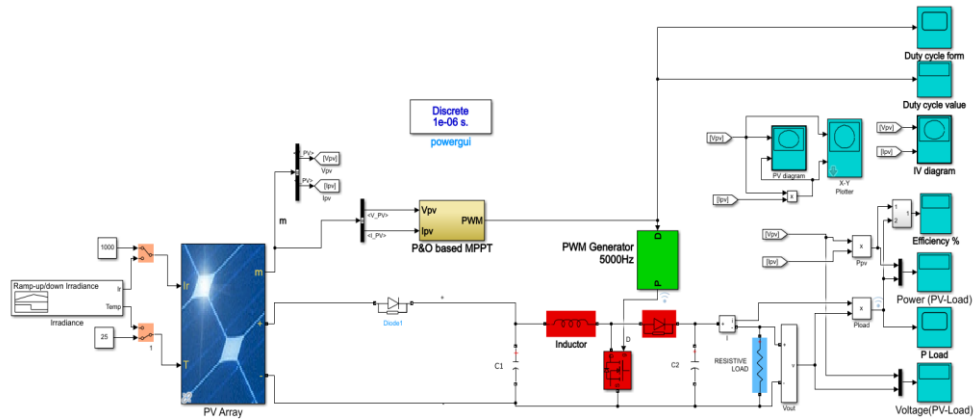


Figure 5. Matlab/Simulink-developed photovoltaic system

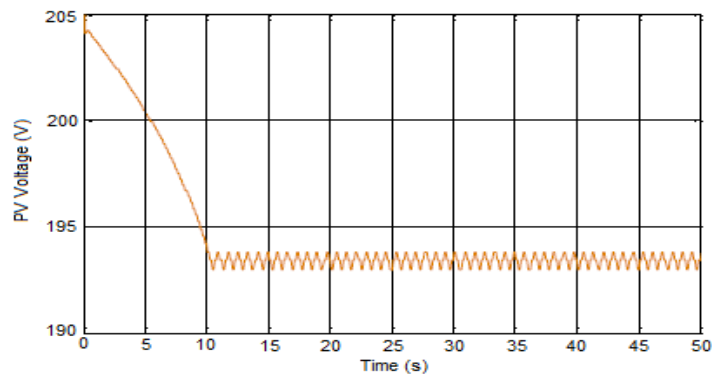


Figure 6. Output voltage of the PV array V_{PV}

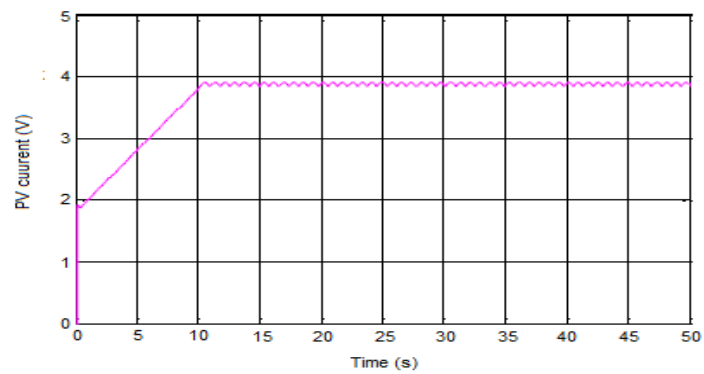


Figure 7. PV array current accurately tracking the Boost converter input current reference ($I_{PV} = I_{ref} = 3.8 A$)

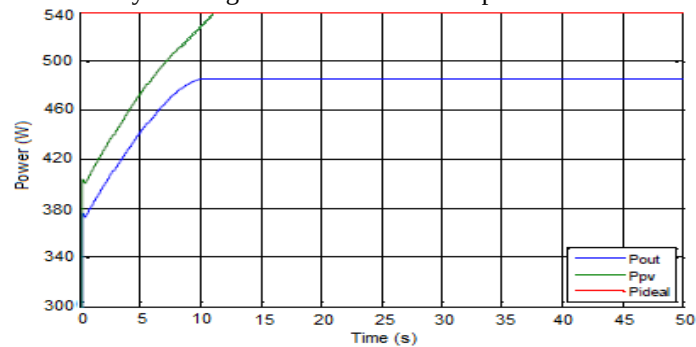


Figure 8. Comparison of PV array output power (P_{pv}) with ideal power (P_{ideal}) and maximum power point output (P_{out})

V.2. Shunt active power filter

The system was modeled and simulated using MATLAB's Simulink toolbox, incorporating the P-Q algorithm in conjunction with a Sliding Mode Controller (SMC). The P-Q algorithm was employed to decompose the load current into its active and reactive components, facilitating effective compensation of reactive power and suppression of harmonic distortions in the distribution network. Subsequently, the sliding mode controller was applied to ensure robust control performance and maintain system stability under varying dynamic conditions.

The key system parameters used in the simulation kept consistent across all evaluated scenarios are listed in Table II. These parameters are critical for accurately capturing the system's dynamic behavior and validating the performance of the proposed control strategy.

Table 1. Simulation Parameters Consistent Across the Applications Analyzed

Parametres	Numerical values
V_s	230 V
f	50 Hz
L_s	19.4 μ H
R_s	0.25 m Ω
L_{dc}	20 mH
R_{dc}	6.5 Ω
$U_{c1} = U_c/4$	210 V
L_f	1.5 mH
L_c	1.5 mH

V.3. Characteristics of the source current before active filtering

The load current waveforms prior to the activation of the Shunt Active Power Filter (SAPF) are shown in Figures 9 and 10. As illustrated in Figure 10, symmetrical distortion is evident in phase current i_{ca} , beginning at the midpoint of the waveform period. This symmetry suggests the absence of even-order harmonics (such as the 2nd and 4th), with the harmonic content predominantly consisting of components of the form $6h \pm 1$.

This observation is further supported by the harmonic spectrum analysis of i_{ca} , also presented in Figure 10, which displays the first 30 significant harmonic components. The Total Harmonic Distortion (THD) of i_{ca} is calculated to be 19.99% over an observation window of 0.1 seconds, highlighting the presence of substantial harmonic distortion and emphasizing the necessity for active filtering to ensure power quality improvement.

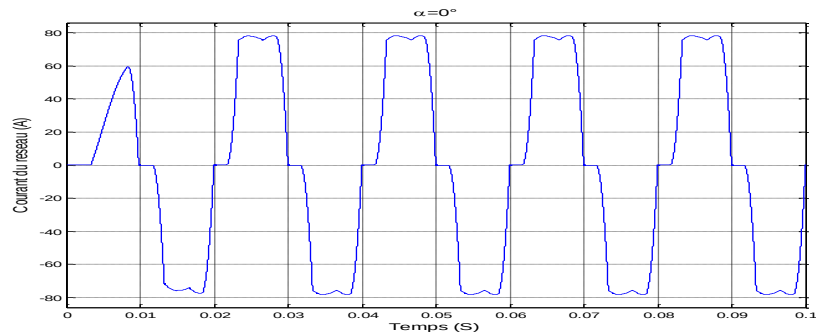


Figure 9. Waveform of phase current i_{ca} before active filtering

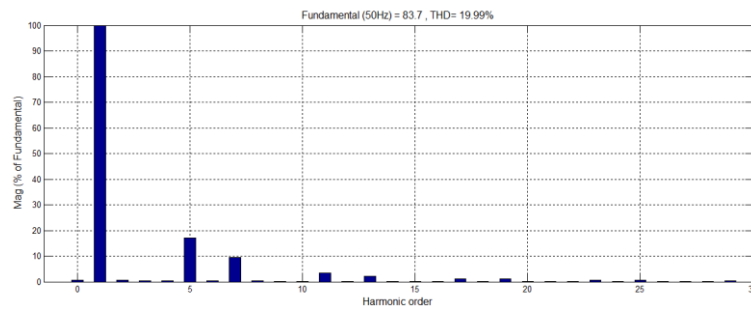


Figure 10. Harmonic spectrum of phase current i_{ca}

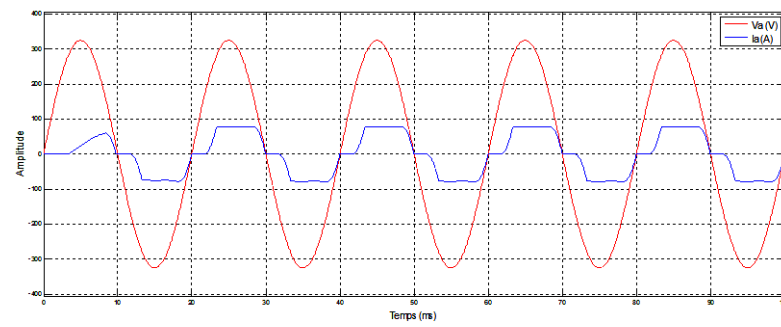


Figure 11. Load current i_{ca} and source voltage v_{sa} waveforms before active filtering

V.4. Characteristics of source current after active filtering

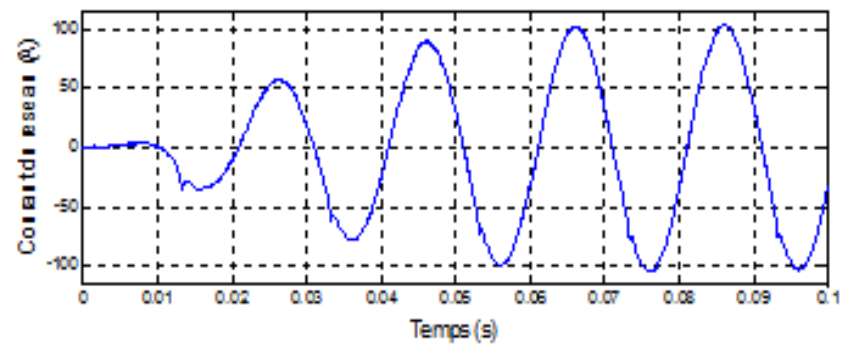


Figure 12. Supply current waveform after active filtering

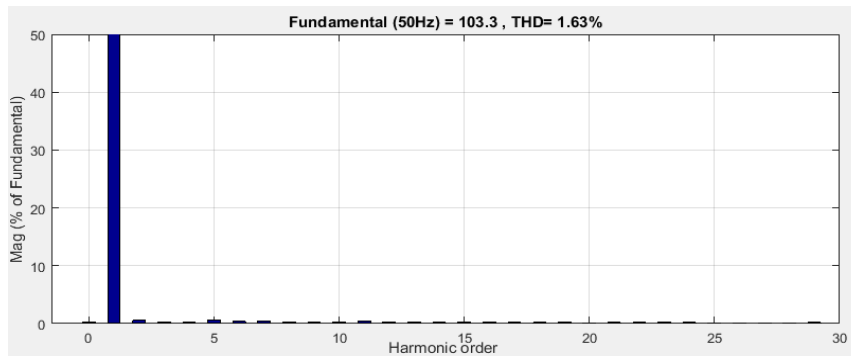


Figure 13. Harmonic spectrum of phase current i_{ca} after compensation

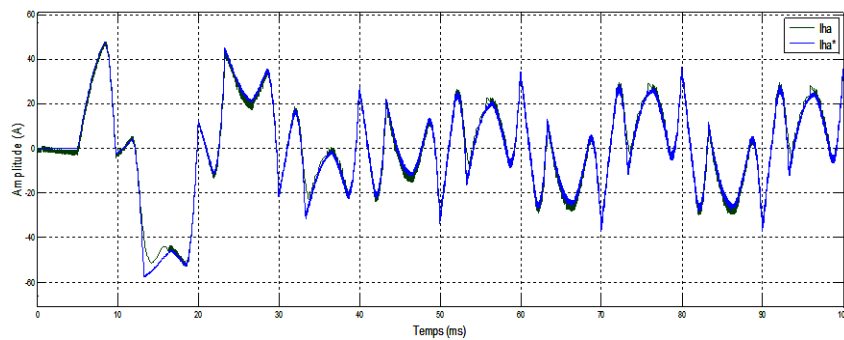


Figure 14. APF output current and its reference using sliding mode controllers

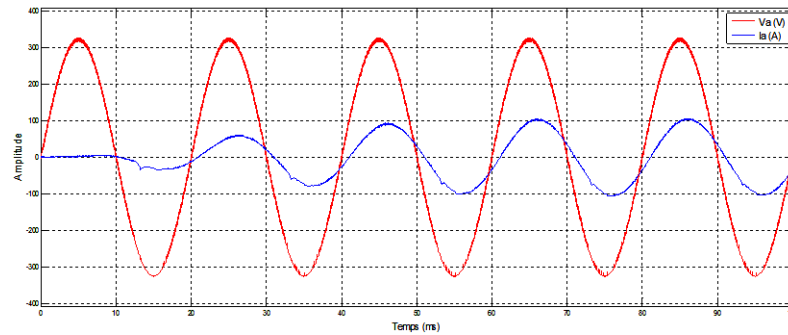


Figure 15. Source current and voltage after harmonic compensation

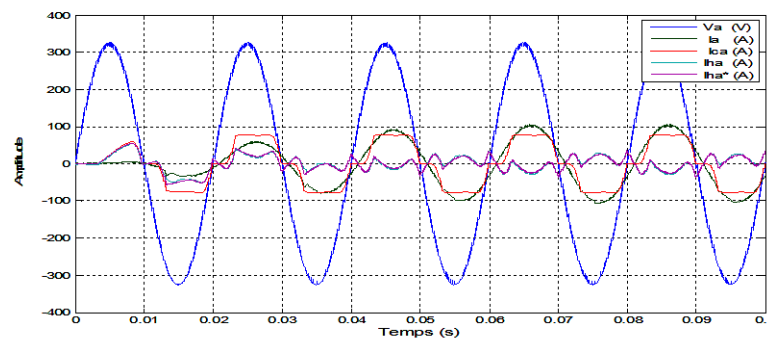


Figure 16. Nonlinear load current i_{ca} , source current i_{sa} , and active filter current i_{fa}

VI. Conclusion

This study has demonstrated the effectiveness of a five-level Shunt Active Power Filter (SAPF) controlled by a Sliding Mode Controller (SMC) in significantly mitigating harmonic distortion. The implementation of the proposed system led to a notable reduction in Total Harmonic Distortion (THD), from 19.99% to 1.63%, highlighting the strong filtering capabilities of the solution. Additionally, the improved alignment between the voltage and current waveforms now nearly in phase confirms an enhancement in the system's power factor.

Future work will focus on extending this research by exploring alternative multilevel inverter topologies, particularly by varying the number of inverter levels. A comparative performance analysis will be conducted to determine the most effective configurations. Moreover, we aim to test the system under more severe harmonic conditions, where THD exceeds 19.99%, in order to evaluate the robustness and adaptability of the proposed control strategy in highly distorted environments.

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