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A Comprehensive Approach for Designing a SAPF to Removing Current and Voltage Harmonics

[1]Ajay Digambar Takalkar, [2]Sarvesh Pratap Singh
[1]M. Tech. Scholar, 2Associate Professor,
[1]Department of Electrical Engineering,
[1]School of Research & Technology, People's University, Bhopal, India

Abstract : This paper presents a comprehensive study to design a shunt active power filter (SAPF) that effectively removes voltage and current harmonics, thus meeting the power quality requirements of the utility grid supply. The design incorporates a proportional-integral (PI) controller for DC-link voltage regulation, and the extraction of reference currents is based on the instantaneous reactive power theory. Hysteresis current control is employed to generate gate signals for controlling the 2-level voltage source inverter (VSI) switches. The SAPF design is implemented and simulated using MATLAB, Simulink block sets, considering both uneven nonlinear loads. Simulation results demonstrate that the projected filter successfully reduces harmonic distortion below the levels specified by the IEEE-519 std.

***IndexTerms* - SAPF, Reactive Power, Power Quality, VSI**

I. INTRODUCTION

Nonlinear electrical devices, commonly found in residential and industrial applications worldwide, rely heavily on power electronic switches. However, these devices contribute to power quality issues such as harmonic distortion, voltage fluctuations, and noise [1]. Harmonic distortion in low-voltage distribution systems can lead to power losses, overheating, insulation failures, and even power system failures. Consequently, addressing power quality problems has become a significant concern for utility companies and customers [2]. To regulate the injection of harmonic currents, the IEEE-SA has established standards for harmonic limitations, specifying a total harmonic distortion (THD) limit of 5%. This necessitates the implementation of power filters.

Active Power filters are efficient technologies extensively halp to mitigate harmonic distortion. Traditional approaches involve series and shunt passive filters integrated into the distribution network for enhanced power quality [3]. However, designing an effective passive filter for eliminating harmonic current distortion in industrial nonlinear loads connected to a stable power supply is challenging. Passive filters have drawbacks, including size, susceptibility to resonance, instability, and limited flexibility [4]. In contrast, active power filters (APFs) with voltage source inverters (VSIs) have emerged as an alternative, overcoming these limitations. APFs offer superior filtering accuracy, fast response, and flexibility, making them an best explanation for power quality issues [5].

The effectiveness of SAPF in reducing harmonics depends on current sensing, compensation control algorithms, and methods for determining reference compensation currents. The instantaneous reactive power theory, proposed by [6], is commonly used for controlling reference compensation currents. Researchers have presented various techniques for extracting components, determining reference currents, and regulating DC-link capacitor voltage. These techniques include modified versions of the P-Q theory, strategies for minimizing harmonic currents under unbalanced voltage conditions, eliminating harmonic distortion on the source side, and preventing harmonic propagation [7].

The literature review reveals a research gap in the design of the proportional-integral (PI) controller for shunt active power filters (SAPFs) and their application in power quality improvement [1], [8]. This study aims to bridge this gap by developing a Simulink model of a PI-based SAPF that utilizes the instantaneous reactive power theory for reference current extraction. The proposed harmonic current compensation strategy is implemented in a three-phase three-wire power system, considering both balanced and unbalanced nonlinear loads. The paper provides detailed procedures for developing the SAPF model and demonstrates its effectiveness in improving power quality.

The subsequent section explains the operational principle of the SAPF, discusses the methodology and details of the harmonics extraction algorithm used in the proposed system, and presents and discusses the simulation results in Section 3. Finally, Section 4 concludes the study by summarizing the findings.

II. MODELING AND CONTROL TECHNIQUE:

The schematic of proposed system presented in the Fig. 1.

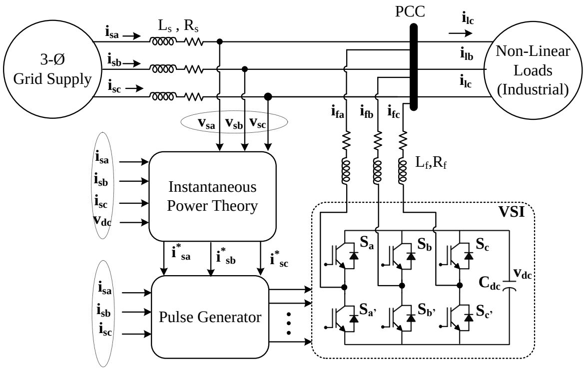


Fig. 1 Schematic configuration of a 3-Ø, SAPF

The control scheme of the SAPF employs the p-q algorithm, which utilizes α-β modulation principles to generate reference current signals. The three-phase currents (ia, ib, ic), source voltages (vsa, vsb, vsc), and DC bus voltage (vdc) are sensed as feedback signals for the active filter. The control scheme, based on the instantaneous reactive power theory, is illustrated in Fig 2.

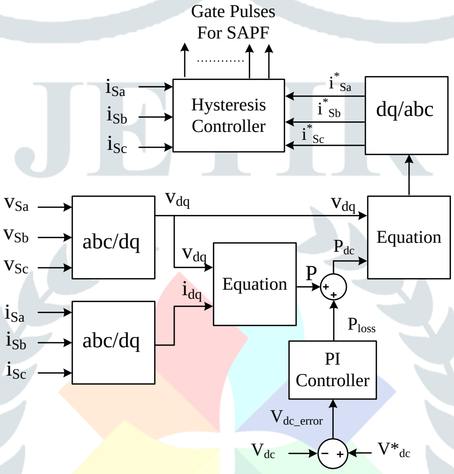


Fig. 2 Generating reference currents using instantaneous power theory

$$\left.\begin{aligned} v_{Sa} &= \mathrm{Sin}(\omega t) \\ v_{Sb} &= \mathrm{Sin}(\omega t - 120^\circ) \\ v_{Sc} &= \mathrm{Sin}(\omega t + 240^\circ) \end{aligned}\right\} \quad (1)$$

Similarly for current,

$$\left.\begin{aligned} i_{Sa} &= \mathrm{Sin}(\omega t) \\ i_{Sb} &= \mathrm{Sin}(\omega t - 120^\circ) \\ i_{Sc} &= \mathrm{Sin}(\omega t + 240^\circ) \end{aligned}\right\} \quad (2)$$

From equation (1)

$$v_d = \sqrt{\frac{2}{3}}\left(v_{Sa} - \frac{v_{Sb}}{2} - \frac{v_{Sc}}{2}\right) \quad (3)$$

$$v_q = \sqrt{\frac{2}{3}}\left[\sqrt{3}\left(\frac{v_{Sb}}{2} - \frac{v_{Sc}}{2}\right)\right] \quad (4)$$

Similarly from equation

$$i_d = \sqrt{\frac{2}{3}}\left(i_{Sa} - \frac{i_{Sb}}{2} - \frac{i_{Sc}}{2}\right) \quad (5)$$

$$i_q = \sqrt{\frac{2}{3}}\left[\sqrt{3}\left(\frac{i_{Sb}}{2} - \frac{i_{Sc}}{2}\right)\right] \quad (6)$$

$$P = v_d * i_d + v_q * i_q \quad (7)$$

$$Q = v_d * i_q - v_q * i_d \tag{8}$$

$$P_{dc} = P_{loss} + P \tag{9}$$

To estimate Pdc, the sensed voltage V_{dc} across the SAPF is compared with the desired reference voltage V_{dc}*. The difference between these two voltages, known as the DC voltage error V_{DC_error}, is used for further calculations.

$$V_{dc\_error} = V_{dc}^{*} - V_{dc} \tag{10}$$

To maintain a steady DC bus voltage, the error signal is fed into a proportional-integral (PI) controller. The output power of the control system is then determined by this controller.

$$P_{loss} = \left(Kp + \frac{K_I}{s} \right) V_{dc\_error} \tag{11}$$

The Proportional-Integral (PI) controller utilizes a constant, Kp, to represent the proportional gain, and Ki is the symbolic representation of the integral gain. The controlled output power of the PI controller is denoted as Pdc.

The equation (12) illustrates the reference direct and quadrature components of the current.

$$i_d^* = \frac{v_d * P_{dc}}{v_d^2 + v_q^2}, i_q^* = \frac{v_q * P_{dc}}{v_d^2 + v_q^2}, \tag{12}$$

$$\left. \begin{aligned} i_{Sa}^* &= \sqrt{\frac{2}{3}} * i_d \\ i_{Sb}^* &= \sqrt{\frac{2}{3}} \left(-\frac{i_d}{2} + \frac{\sqrt{3}}{2} i_q \right) \\ i_{Sc}^* &= \sqrt{\frac{2}{3}} \left(-\frac{i_d}{2} - \frac{\sqrt{3}}{2} i_q \right) \end{aligned} \right\} \tag{13}$$

The carrier-less hysteresis-based PWM current controller utilizes the estimated reference currents (isa*, isb*, isc*) and sensed actual currents (isa, isb, isc) to generate switching signals for the PWM converter. The switches' operation is based on the difference between the reference current and the actual current. Activating the appropriate switches increases or decreases the current in specific phases. A lockout delay prevents shoot-through or cross-conduction. After isolation and amplification, the switching signals are sent to the switching devices. This allows current to flow through the filter inductor Lf, compensating for load harmonic current and reactive power while drawing only active power from the source.

III. RESULTS AND DISCUSSION

A MATLAB/Simulink simulation model is created to evaluate the performance of the SAPF. The simulation focuses on balanced load conditions and assesses the SAPF's ability to cancel harmonic currents in the source and compensate for reactive power. The steady-state behavior is analyzed using FFT analysis of the source current. The effectiveness of the SAPF is evaluated by monitoring the active power loss in the DC capacitor, which is controlled by a PI controller.

The study examines the effectiveness of an active filter in compensating for harmonics and reactive power in the presence of uncontrolled diode rectifiers with R-L elements on their DC side, which are commonly used as nonlinear loads. Simulation studies are conducted with a 5 kVA compensation capacity, and the specific parameters used in the simulations are presented in Table 1.

Table 1: Simulation parameters for conventional and MLI based SAPF

Source voltage vs and frequency fs	230, 50 Hz
Source Resistance Rs and Inductance Ls	0.35 Ω, 0.75 mH
AC side Inverter: Resistance Rf and Inductance Lf	0.45 Ω, 3.4 mH
Capacitor across DC link	2000 μF
DC reference voltage vdc_ref	680 V

Figure 3 illustrates the transient behavior of the SAPF in a balanced load scenario. At t1=0.06 sec, a non-linear industrial load is connected, resulting in distorted load current. However, the source current remains sinusoidal, indicating effective compensation by the SAPF. The figure displays the source voltage, filter voltage, source current, load current, and DC link voltage of the SAPF, providing insights into its performance.

The VSI inverter consists of IGBT/Diodes switches. Upon connecting the three-phase supply to the system, the DC capacitor connected to the VSI begins to charge. At t1=0.06 sec, when the SAPF is activated by providing gate pulses to the IGBTs of the VSI, the DC capacitor voltage gradually reaches the desired reference value of 680 V, as depicted in Fig 3. Despite disturbances, such as the connection of a nonlinear load on the distribution side, the DC bus voltage across the SAPF remains close to the reference value, ensuring stable operation.

Fig. 4 illustrates the response in steady-state of various parameters for a conventional 2-level SAPF operating at 230 V phase voltage. This includes source voltages (vsabc), filter voltage (vfabc), source currents after compensation (isabc), load currents (ilabc), compensating current (ifabc), and capacitor voltage (vdc). Notably, the voltage across the DC link of the inverter is approximately twice the source voltage, approximately 680 V. The harmonic spectrum of the load current and compensated source current for phase 'a' is presented in Fig. 5(a) and (b) respectively. The analysis reveals that the source current THD complies with IEEE standards, remaining below the 5% limit.

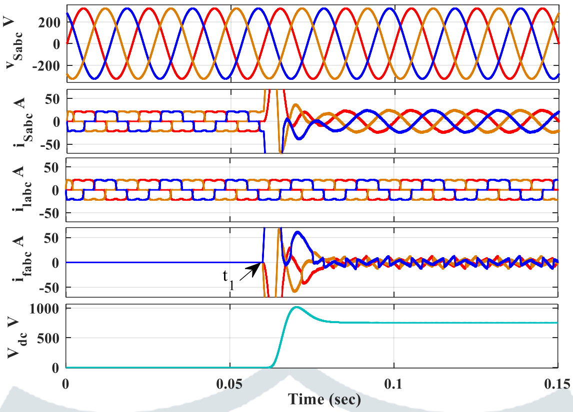


Fig.3 Measured electrical parameters of the VSI include source voltages, filter currents, source currents, load currents, filter currents, and DC link voltages.

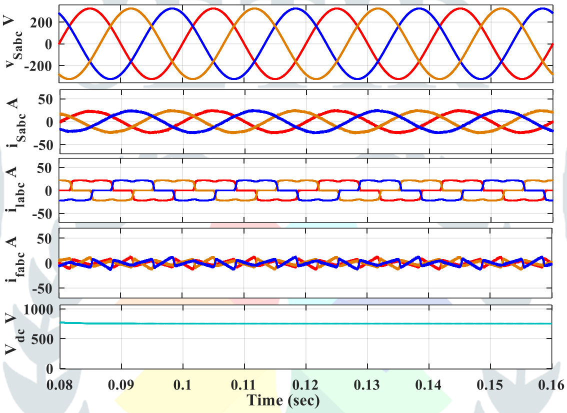
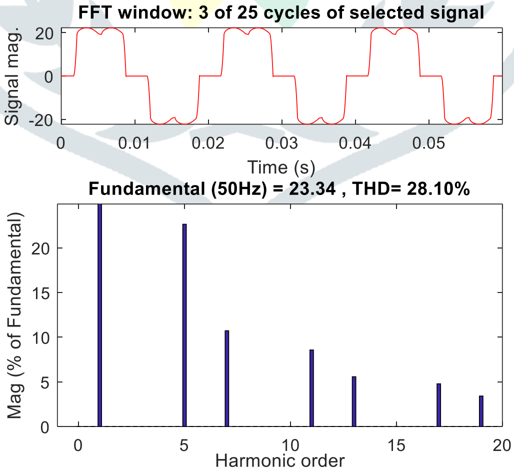
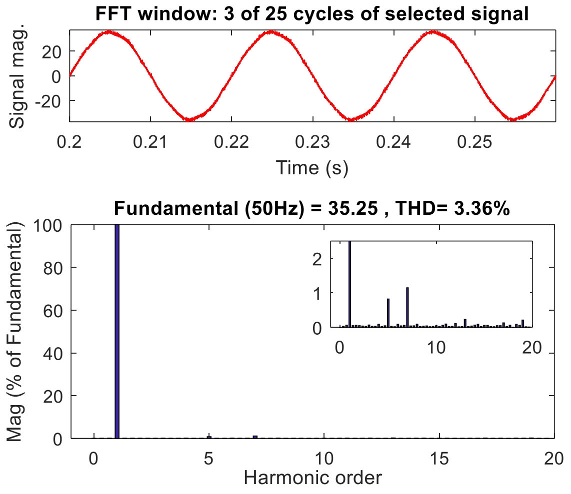


Fig. 4 Simulated waveforms of a conventional SAPF, displayed in order from top to bottom: source voltages (vsabc), filter voltages (vfabc), source currents after compensation (isabc), load currents (ilabc), filter currents (icabc), and capacitor voltage (vdc)



(a)



(b)

Fig. 5 Frequency spectrum analysis of phase 'a': (a) load current (ila), and (b) source current (isa) after compensation.

IV. CONCLUSION:

This study emphasizes the design and simulation of a 3-Ø 4-wire SAPF employing the instantaneous reactive power theory and hysteresis-PI control algorithm. The performance of the filter in mitigating current harmonics is assessed under both balanced and unbalanced nonlinear load scenarios. Furthermore, a comparative analysis is conducted to evaluate its effectiveness compared to other existing techniques. Simulation results demonstrate that the proposed SAPF successfully restores distorted source currents to sinusoidal waveforms and significantly reduces harmonics below IEEE standard limits. FFT spectrum analyses show substantial reduction in total harmonic distortion (THD) for both balanced and unbalanced systems. The proposed SAPF outperforms existing methods in mitigating harmonics in various load conditions.

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