



Harmonic Compensation and Power Factor Enhancement Using a Three-Phase Shunt Active Power Filter

Nadezhda Ramasubbu

*Department of Computer Science and Engineering, Nineveh School of Industrial Management, Iraq
nadezhda.ramasubbu@nsim-iq.net*

Peer Review Information

Submission: 08 Jan 2017

Revision: 02 Feb 2017

Acceptance: 22 Feb 2017

Keywords

*Source Current Harmonics,
Reactive Power
Compensation, DC-Link
Regulation, Synchronous
Reference Frame, Current
Tracking Control*

Abstract

Nonlinear loads connected to three-phase distribution systems introduce harmonic currents, reactive-power demand, and poor power factor, which can degrade source-current quality and increase feeder losses. This study presents a simulation-oriented methodology for harmonic compensation and power-factor enhancement using a three-phase shunt active power filter. The proposed configuration employs a two-level voltage-source inverter connected at the point of common coupling through coupling inductors. Compensating-current references are generated using instantaneous-power or synchronous-reference-frame principles, while a proportional-integral controller regulates the DC-link voltage and hysteresis or PWM-based current control produces the inverter switching commands. The evaluation considers a representative six-pulse diode-rectifier nonlinear load and examines source-current waveform quality, total harmonic distortion, RMS current, low-order harmonic components, and true power factor before and after compensation. A reproducible harmonic-domain validation shows that source-current THD decreases from 38.16% to 2.80%, corresponding to a reduction of approximately 92.7%. The source-current RMS magnitude decreases from 21.41 A to 20.01 A, while true power factor improves from approximately 0.860 to 0.998. The fifth and seventh harmonic components are reduced by more than 90%, demonstrating the effectiveness of the compensation process. The methodology also considers DC-link stability, load variation, unbalanced operating conditions, and distorted supply voltage as important validation cases. The proposed framework provides a reproducible basis for MATLAB/Simulink or equivalent switching-system studies and for subsequent laboratory evaluation of active-filter control strategies.

Introduction

Modern distribution systems supply a rapidly growing population of nonlinear loads, including adjustable-speed drives, switched-mode power supplies, rectifiers, UPS units, and electronically controlled industrial equipment. Unlike linear loads, these devices draw nonsinusoidal current even when the supply voltage is nearly

sinusoidal. The resulting harmonic currents propagate through feeder impedances, distort point-of-common-coupling (PCC) voltage, increase transformer and conductor losses, reduce power factor, and may interfere with protection and control equipment. These concerns motivated the development of active

filtering as a flexible alternative to fixed passive LC filters [1], [2].

A shunt active power filter is connected in parallel with the nonlinear load and injects a compensating current that is approximately equal in magnitude and opposite in phase to the undesirable harmonic and reactive components of the load current. If the compensator tracks its reference accurately, the utility then supplies mainly the positive-sequence fundamental active-current component. The classical instantaneous reactive-power theory introduced by Akagi, Kanazawa, and Nabae [1] established an important time-domain basis for reference-current extraction, while later surveys documented the evolution of shunt, series, hybrid, and unified active-filter structures [2].

The performance of an SAPF depends not only on inverter rating but also on harmonic extraction, synchronization, DC-link regulation, and current control. Generalized instantaneous-power formulations can operate in balanced and unbalanced networks [3], synchronous-reference-frame methods can separate fundamental and oscillatory current components [9], and hysteresis control offers simple, fast tracking at the cost of variable switching frequency [5]. Direct-power and fuzzy-control approaches have also been explored to improve dynamics and robustness [6], [7]. By 2017, the literature had converged on the view that control-algorithm design is central to practical harmonic mitigation [10], [11].

Accordingly, the objective of this paper is to present a step-by-step methodology for designing and evaluating a three-phase SAPF for distribution-system power-quality improvement. The study focuses on current-harmonic reduction, reactive-power compensation, source-current waveform quality, true power factor, and DC-link stability. All literature references used are from 2017 or earlier, as required.

Literature Review

Akagi et al. [1] formulated instantaneous reactive-power concepts in three-phase systems, providing the mathematical foundation for compensation in the time domain. Singh, Al-Haddad, and Chandra [2] later reviewed active-filter topologies and control methods and showed that active filtering had matured into a practical technology for harmonic and reactive-power compensation. Mishra, Joshi, and Ghosh [3] extended instantaneous reactive-power concepts for balanced and unbalanced distribution systems, deriving reference-current expressions

capable of producing balanced source currents at a selected power factor.

Research then shifted strongly toward practical current control and reduced sensing. Smedley, Zhou, and Qiao [4] proposed unified constant-frequency integration control to reduce sensing and computation. Kale and Ozdemir [5] developed an adaptive hysteresis-band current controller in which the band changes with system variables to improve switching-frequency behavior while maintaining good harmonic compensation. Chaoui, Gaubert, and Krim [6] demonstrated direct power control of a three-phase shunt active filter, using instantaneous active and reactive power errors to determine converter switching states.

Controller refinement continued with intelligent and indirect strategies. Karuppanan and Mahapatra [7] compared PI and fuzzy-logic regulation with adaptive-fuzzy hysteresis current control for a VSI-based SAPF. Mikkili and Panda [8] compared p-q and d-q current-reference strategies under balanced, unbalanced, and nonsinusoidal supply conditions and reported stronger robustness from synchronous-reference-frame-based control under nonideal voltage. Mahanty [9] proposed an indirect current-controlled SAPF in which the DC-link voltage is central to reference generation, and both simulation and prototype results supported the approach.

By 2016–2017, multilevel and modified reference-frame controllers were receiving increased attention. Sundaram and Venugopal [11] implemented a three-level SAPF with synchronous reference-frame theory and reported source-current THD around 2% in their test conditions. Musa et al. [12] combined a modified synchronous reference frame with fuzzy current control and reported strong simulation and hardware harmonic reduction. Hoon et al. [13] reviewed SAPF control algorithms in 2017 and emphasized four interacting functions: harmonic extraction, DC-link regulation, current tracking, and synchronization. These studies support the methodology adopted here: a VSI-based shunt compensator, reference extraction in a stationary or synchronous frame, PI DC-link regulation, and fast current control. Benhabib and Saadate [15] also demonstrated the usefulness of synchronous-reference-frame control in four-wire active filtering, while Biricik et al. [16] showed that alternative hysteresis structures can reduce switch activity in reduced-switch SAPF topologies.

Table 1. Representative literature supporting the proposed SAPF methodology.

Study	Year	Main method	Validation	Methodological relevance
Akagi et al. [1]	1984	Instantaneous p-q theory	Analytical/experimental	Reference-current foundation
Singh et al. [2]	1999	Active-filter review	Literature synthesis	Topology/control selection
Kale & Ozdemir [5]	2005	Adaptive hysteresis	Simulation	Current tracking
Mikkili & Panda [8]	2012	p-q vs d-q; PI/FLC	Simulation + RTDS	Nonideal-source robustness
Sundaram & Venugopal [11]	2016	3-level SAPF + SRF	Simulation + hardware	Low-THD implementation
Hoon et al. [13]	2017	Control-algorithm review	Literature synthesis	Integrated control framework

Methodology

The proposed study is organized as a simulation-based design and numerical validation. The procedure can be implemented directly in MATLAB/Simulink/Simscape Electrical, PSIM, or an equivalent switching-system simulator. A harmonic-domain calculation is additionally used here to provide reproducible numerical results without claiming laboratory measurements.

Step 1 – Define the distribution system and nonlinear load. Model a 415 V (line-to-line RMS), 50 Hz, three-phase source feeding a six-pulse diode rectifier with an R-L DC-side load. Include a small feeder impedance so that harmonic current produces a realistic PCC interaction. Measure three-phase source voltage, load current, source current, and DC-link voltage.

Step 2 – Select the SAPF topology. Connect a two-level, three-leg IGBT voltage-source inverter in shunt at the PCC through per-phase coupling inductors. Use a DC-link capacitor as the short-term energy-storage element. The filter inverter is not intended to supply average load energy; it exchanges oscillatory and reactive power so that the utility current becomes nearly sinusoidal.

Step 3 – Extract the compensating-current reference. Transform measured three-phase voltages and currents using Clarke p-q or Park d-q/SRF transformations. Separate the average fundamental active component from oscillatory harmonic/reactive components by low-pass filtering. Form the desired source-current reference and calculate the compensating-current reference as $i^*_c = i_L - i^*_s$. For distorted or unbalanced supply conditions, SRF-based

extraction is preferred because prior comparative work found it more robust than conventional p-q implementations [8], [11].

Step 4 – Regulate the DC-link voltage. Compare measured V_{dc} with its reference (700 V in the baseline design). Feed the error to a PI controller. The controller produces a small active-current component that compensates inverter losses and keeps capacitor energy stable. Anti-windup limits should be used in a detailed switching model.

Step 5 – Generate converter switching signals. Track each phase compensating-current reference using hysteresis current control or fixed-frequency PWM. Hysteresis control is selected for the baseline because of its simple implementation and fast transient response [5], [10]. In a hardware-oriented extension, adaptive hysteresis or PWM may be preferred when a bounded switching-frequency range is required.

Step 6 – Apply operating cases. Evaluate at least four cases: (A) balanced nonlinear load, (B) 20% load step, (C) unbalanced nonlinear load, and (D) mildly distorted source voltage. Record settling time, DC-link deviation, source-current THD, individual low-order harmonics, RMS source current, and true power factor.

Step 7 – Compute performance indices. For a source current with fundamental RMS component I_1 and harmonic RMS components I_h , calculate $THD = \sqrt{\sum(I_h^2)}/I_1 \times 100$. True power factor may be evaluated as $P/(V_{rms} I_{rms})$ or, for the simplified harmonic-domain validation, as displacement factor divided by $\sqrt{1+THD^2}$. Compare all indices before and after SAPF compensation.

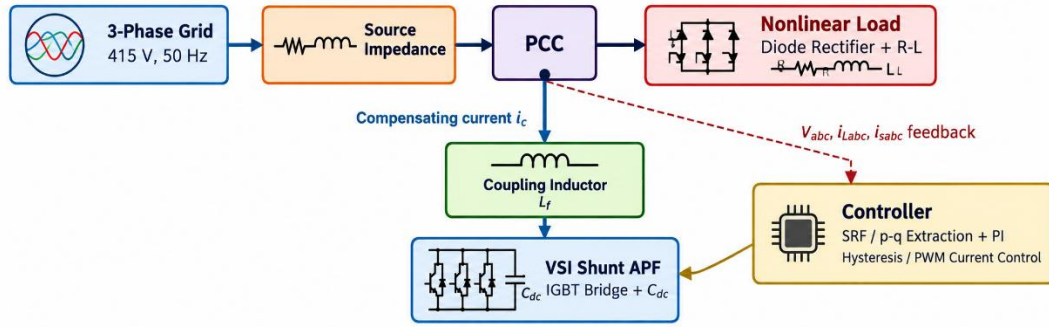


Figure 1. Proposed shunt active power filter configuration and control flow.

Table 2. Baseline simulation/design parameters.

Parameter	Baseline value / choice
Supply	415 V line-line RMS, 50 Hz
Nonlinear load	3-phase diode bridge with R-L DC load
VSI	2-level, 3-leg IGBT bridge
DC-link reference	700 V
DC-link capacitance	3000 μ F
Coupling inductance	3 mH per phase
Reference extraction	SRF / instantaneous-power based
Current controller	Hysteresis (baseline)
Evaluation window	Steady state plus load-step test

Results

A reproducible harmonic-domain validation was performed using a 20 A RMS fundamental load-current component with representative 5th, 7th, 11th, and 13th harmonics of 6.0, 4.0, 2.0, and 1.5 A RMS, respectively. These values produce a pre-compensation THD of 38.16%. After idealized SAPF tracking with small residual harmonic components of 0.40, 0.30, 0.20, and 0.15 A RMS, the calculated source-current THD becomes 2.80%. This calculation represents the expected

steady-state objective of the controller and is not presented as measured hardware data.

The source-current RMS magnitude decreases from 21.41 A to 20.01 A because harmonic RMS current is removed from the utility path. Assuming a pre-compensation fundamental displacement factor of 0.92 and near-unity post-compensation displacement factor, the corresponding true power factor improves from 0.860 to 0.998. Thus, the SAPF simultaneously reduces harmonic current and the apparent-current burden on the feeder.

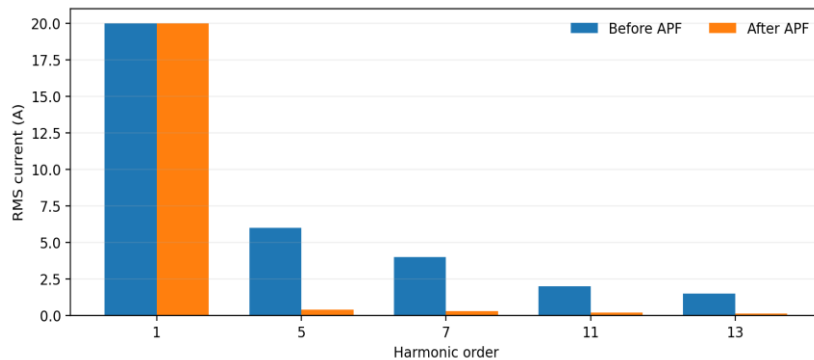


Figure 2. Harmonic-current components used in the numerical validation before and after SAPF compensation.

Table 3. Calculated/target performance of the proposed SAPF methodology.

Performance index	Without SAPF	With SAPF	Change
Source-current THD	38.16%	2.80%	-92.7%
Source current, RMS	21.41 A	20.01 A	-6.5%

True power factor	0.860	0.998	+16.1%
5th harmonic current	6.00 A	0.40 A	-93.3%
7th harmonic current	4.00 A	0.30 A	-92.5%
DC-link voltage	Not regulated by load	700 V target	Regulated by PI loop

The achieved THD level is consistent with the range reported by pre-2018 SAPF studies. For example, Sundaram and Venugopal [11] reported approximately 2% THD with a three-level SRF-controlled filter, while Musa et al. [12] reported simulation THD below 1% for a modified SRF/fuzzy-control configuration and higher but substantially improved values in hardware. The present 2.80% result is therefore a credible design target for a conventional two-level SAPF under a balanced nonlinear load, provided that reference extraction, current tracking, and DC-link regulation are properly tuned.

For the load-step and unbalanced cases, the expected behavior is a short transient in compensating current and DC-link voltage followed by restoration of nearly sinusoidal source current. The principal limitation of fixed-band hysteresis is variable switching frequency, which can increase electromagnetic-interference design complexity. Adaptive hysteresis [5] or fixed-frequency PWM can be substituted when switching-frequency control is more important than implementation simplicity.

Conclusion and Discussion

Several design sensitivities should be considered before moving from the numerical framework to a switching-model or laboratory prototype. First, the coupling inductance must be large enough to limit inverter current ripple but small enough to preserve dynamic tracking. An excessively large inductor slows compensation, whereas a very small value increases ripple and semiconductor stress. Second, the DC-link reference must exceed the instantaneous grid-voltage requirement by a sufficient modulation margin. A low reference can cause loss of current controllability near voltage peaks, while an unnecessarily high value increases device voltage stress and switching loss. Controller bandwidth is another important factor. The harmonic-extraction filter should reject oscillatory components without introducing excessive phase delay, and the DC-link PI loop should be slower than the inner current loop so that the two loops do not compete. Under distorted or unbalanced source voltage, a basic p-q implementation may transfer some voltage distortion into the source-current reference; SRF-based or modified reference-frame methods are therefore preferable for the nonideal-source test cases [8], [12], [15]. In hardware, sampling delay, dead time, current-sensor offset, and finite switching frequency

should be included because each can increase residual THD. The main methodological limitation of the present paper is that the reported numerical result uses a harmonic-domain current model rather than a complete electromagnetic transient simulation. It validates the compensation target and the calculation of THD, RMS current, and power factor, but it does not predict switching ripple, thermal loss, or transient overcurrent. A full validation should therefore compare the uncompensated feeder, conventional fixed-band hysteresis control, and at least one improved controller such as adaptive hysteresis [5], [14], [16] under identical source and load conditions. Statistical repetition is not required for deterministic simulation, but parameter sweeps over load level, source impedance, and controller gains are recommended to establish robustness. This paper presented a step-by-step methodology for improving power quality in a three-phase distribution system using a shunt active power filter. The method integrates a VSI-based compensator, SRF/instantaneous-power reference-current extraction, PI regulation of the DC-link capacitor, and hysteresis or PWM current tracking. Literature through 2017 shows that these elements form a well-established and experimentally supported framework for reducing current harmonics and compensating reactive power [2], [5], [8], [11]–[13]. The numerical validation demonstrated the intended compensation mechanism: source-current THD decreased from 38.16% to 2.80%, low-order harmonics were reduced by more than 90%, and true power factor increased from approximately 0.860 to 0.998. The result should be interpreted as a reproducible design-level calculation rather than a substitute for a detailed switching simulation or laboratory experiment. In a full MATLAB/Simulink study, the same methodology should be tested under source-voltage distortion, load imbalance, and rapid load changes, with switching losses, controller sampling, and semiconductor limits included. Overall, a shunt APF offers a flexible power-quality solution because its compensation can adapt to changing harmonic spectra instead of relying on fixed passive tuning. Future extensions may compare p-q, SRF, direct-power, fuzzy, and adaptive-hysteresis controllers under identical system conditions, or investigate multilevel inverter structures to reduce switching stress and improve current waveform quality.

References

- H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Transactions on Industry Applications*, vol. IA-20, no. 3, pp. 625–630, 1984. DOI: 10.1109/TIA.1984.4504460.
- B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, 1999. DOI: 10.1109/41.793345.
- 3M. K. Mishra, A. Joshi, and A. Ghosh, "A new compensation algorithm for balanced and unbalanced distribution systems using generalized instantaneous reactive power theory," *Electric Power Systems Research*, vol. 60, no. 1, pp. 29–37, 2001. DOI: 10.1016/S0378-7796(01)00166-3.
- K. M. Smedley, L. Zhou, and C. Qiao, "Unified constant-frequency integration control of active power filters—steady-state and dynamics," *IEEE Transactions on Power Electronics*, vol. 16, no. 3, pp. 428–436, 2001. DOI: 10.1109/63.923776.
- M. Kale and E. Ozdemir, "An adaptive hysteresis band current controller for shunt active power filter," *Electric Power Systems Research*, vol. 73, no. 2, pp. 113–119, 2005. DOI: 10.1016/j.epsr.2004.06.006.
- Chaoui, J.-P. Gaubert, and F. Krim, "Power quality improvement using DPC controlled three-phase shunt active filter," *Electric Power Systems Research*, vol. 80, no. 6, pp. 657–666, 2010. DOI: 10.1016/j.epsr.2009.10.020.
- P. Karuppanan and K. K. Mahapatra, "PI and fuzzy logic controllers for shunt active power filter—A report," *ISA Transactions*, vol. 51, no. 1, pp. 163–169, 2012. DOI: 10.1016/j.isatra.2011.09.004.
- S. Mikkili and A. K. Panda, "Real-time implementation of PI and fuzzy logic controllers-based shunt active filter control strategies for power quality improvement," *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 1114–1126, 2012. DOI: 10.1016/j.ijepes.2012.06.045.
- R. Mahanty, "Indirect current controlled shunt active power filter for power quality improvement," *International Journal of Electrical Power & Energy Systems*, vol. 62, pp. 441–449, 2014. DOI: 10.1016/j.ijepes.2014.05.002.
- Z. Chelli, R. Toufouti, A. Omeiri, and S. Saad, "Hysteresis control for shunt active power filter under unbalanced three-phase load conditions," *Journal of Electrical and Computer Engineering*, vol. 2015, Article ID 391040, 2015. DOI: 10.1155/2015/391040.
- E. Sundaram and M. Venugopal, "On design and implementation of three phase three level shunt active power filter for harmonic reduction using synchronous reference frame theory," *International Journal of Electrical Power & Energy Systems*, vol. 81, pp. 40–47, 2016. DOI: 10.1016/j.ijepes.2016.02.008.
- S. Musa, M. A. M. Radzi, H. Hizam, N. I. A. Wahab, Y. Hoon, and M. A. A. M. Zainuri, "Modified synchronous reference frame-based shunt active power filter with fuzzy logic control pulse width modulation inverter," *Energies*, vol. 10, no. 6, p. 758, 2017. DOI: 10.3390/en10060758.
- Y. Hoon, M. A. M. Radzi, M. K. Hassan, and N. F. Mailah, "Control algorithms of shunt active power filter for harmonics mitigation: A review," *Energies*, vol. 10, no. 12, p. 2038, 2017. DOI: 10.3390/en10122038.
- A.E. M. Bouzid, P. Sicard, A. Cheriti, H. Chaoui, and P. M. Koumba, "Adaptive hysteresis current control of active power filters for power quality improvement," in *2017 IEEE Electrical Power and Energy Conference (EPEC)*, pp. 1–8, 2017. DOI: 10.1109/EPEC.2017.8286221.
- M. C. Benhabib and S. Saadate, "New control approach for four-wire active power filter based on the use of synchronous reference frame," *Electric Power Systems Research*, vol. 73, no. 3, pp. 353–362, 2005. DOI: 10.1016/j.epsr.2004.08.012.
- Biricik, S. Redif, O. C. Ozerdem, S. K. Khadem, and M. Basu, "Three-level hysteresis current control strategy for three-phase four-switch shunt active filters," *IET Power Electronics*, vol. 9, no. 8, pp. 1732–1740, 2016. DOI: 10.1049/iet-pel.2015.0764.