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Digital Signal Processing Techniques for Active Power Filter-Based Power Quality Improvement

Anup Chandrashekhar Bhogde[1] and Dr. Brijendra Mishra[2]
[1]Research Scholar, Department of Electrical Engineering
[2]Research Guide, Department of Electrical Engineering
Vikrant University, Gwalior, M.P, India

Abstract : *Power quality has become a major concern in modern electrical distribution systems because of the increasing penetration of nonlinear loads, power electronic converters, renewable-energy interfaces, electric-vehicle chargers, adjustable-speed drives, and distributed energy resources. These devices generate harmonic currents, reactive power, current imbalance, voltage distortion, and rapidly changing transient disturbances. Active Power Filters, particularly shunt active power filters, provide a flexible solution because they can generate compensating currents dynamically and thereby reduce harmonic distortion and improve power factor. The effectiveness of an APF, however, depends strongly on its digital signal processing architecture, including disturbance detection, reference-current extraction, synchronization, filtering, current tracking, and switching-signal generation.*

Keywords: Active Power Filter, Digital Signal Processing, Power Quality, Harmonic Mitigation, Wavelet Transform, Predictive Control.

I. INTRODUCTION

The rapid development of power-electronic technology has significantly changed the operating characteristics of modern power systems. Semiconductor converters, variable-frequency drives, switching power supplies, electric-vehicle chargers, photovoltaic converters, battery-storage systems, and other nonlinear devices have increased the occurrence of harmonic currents and other power-quality disturbances. Harmonic distortion can increase losses, overheat electrical equipment, reduce power factor, interfere with sensitive equipment, and decrease the reliability of distribution networks.

Active power filters have consequently become an important technology for dynamic compensation because they can inject a controlled current or voltage that counteracts unwanted components produced by nonlinear loads. Recent reviews classify APFs into shunt, series, hybrid, and other configurations and emphasize their ability to address harmonic currents, reactive power, imbalance, and other power-quality problems dynamically (Das 2021).

The control performance of an APF depends substantially on its ability to identify undesirable signal components accurately and rapidly. This is fundamentally a digital signal-processing problem. A typical digital APF controller samples source voltage, load current, filter current, and DC-link voltage through analog-to-digital converters. The DSP algorithm then separates fundamental and unwanted components, calculates reference compensation signals, regulates the DC-link voltage, and generates switching commands for the voltage-source inverter. Therefore, improvements in DSP algorithms directly influence harmonic compensation, transient response, computational burden, switching frequency, and system stability. Reviews of shunt APF control have shown that the development of reference-current extraction and current-control algorithms has become a central research issue.

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II. MAJOR DIGITAL SIGNAL PROCESSING TECHNIQUES

Table 1. Major DSP Techniques Used in APF-Based Power-Quality Improvement

DSP technique	Main function	Major advantage	Major limitation	Typical APF application
FFT/DFT	Harmonic identification	Accurate frequency-domain analysis	Computational delay and windowing effects	Harmonic monitoring
Instantaneous p-q theory	Reference-current extraction	Simple and fast	Sensitive to distorted/unbalanced conditions	Three-phase SAPF
d-q transformation	Fundamental/harmonic separation	Effective dynamic control	Requires synchronization	Three-phase APF
Low-pass filter	Fundamental extraction	Simple implementation	Phase delay	Conventional APF
Notch filter	Selective frequency rejection	Effective for targeted harmonics	Frequency-specific	Harmonic compensation
Adaptive filtering	Online signal estimation	Handles changing conditions	Parameter/convergence issues	Variable nonlinear loads
Wavelet transform	Time-frequency decomposition	Excellent transient localization	Higher computational requirement	Non-stationary disturbances
Predictive processing	Future-current estimation	Fast dynamic response	Model dependence	High-performance APF
Repetitive control	Periodic harmonic rejection	Strong steady-state harmonic suppression	Periodic-signal dependence	Grid-connected APF
Fuzzy control	Nonlinear decision/control	Robust without precise model	Rule/design complexity	APF current/DC-link control
Neural/neuro-fuzzy control	Adaptive nonlinear control	Learning capability	Training and computational burden	Intelligent APF
PSO/GWO optimization	Parameter optimization	Improved tuning	Optimization computation	Intelligent APF tuning

The table illustrates that no single DSP method is universally optimal. The appropriate technique depends on whether the primary requirement is harmonic identification, transient detection, computational efficiency, robustness, or adaptive operation.

III. FOURIER TRANSFORM-BASED SIGNAL PROCESSING

Fourier Transform methods represent one of the most established approaches to harmonic analysis. The Discrete Fourier Transform and FFT decompose sampled current or voltage signals into their fundamental and harmonic frequency components. This allows the controller to identify individual harmonic orders and calculate their amplitudes and phases.

FFT-based processing is particularly useful where the fundamental frequency is relatively stable and harmonic components are well defined. It is also useful for power-quality monitoring because harmonic spectra can be directly visualized and quantified. However, conventional Fourier analysis assumes a certain degree of signal stationarity. Sudden load changes and transient disturbances can introduce spectral leakage and processing delays.

The increasing need to detect non-stationary disturbances has encouraged researchers to combine Fourier methods with other DSP techniques. Recent power-quality signal-processing literature identifies Fourier, Short-Time Fourier

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Transform, and wavelet-based methods as major approaches for disturbance analysis, while highlighting the importance of time-frequency localization for dynamic events.

IV. WAVELET TRANSFORM-BASED DSP

Wavelet Transform has emerged as an important DSP method for APF applications because electrical disturbances are often non-stationary. Unlike conventional Fourier analysis, which primarily describes frequency content over a window, wavelets provide localized information in both time and frequency.

The Discrete Wavelet Transform decomposes the signal into multiple frequency bands. This enables the controller to distinguish fundamental components, low-order harmonics, high-frequency disturbances, and transient components. Wavelet processing is therefore particularly suitable for voltage sag, swell, transient, switching disturbances, and rapidly changing nonlinear loads.

Kumar and Bansal investigated wavelet-based control for shunt APFs using synchronous-reference-frame-based reference generation and different wavelet families. Their hardware-in-the-loop implementation using an FPGA-based computational platform demonstrated the practical feasibility of wavelet-based APF control and reported differences among Haar, Symlet, Daubechies, and Biorthogonal wavelets.

V. ADAPTIVE FILTERING TECHNIQUES

Adaptive digital filters continuously modify their coefficients according to changes in the input signal. This characteristic is particularly valuable for APFs because nonlinear loads rarely operate under perfectly constant conditions. Load magnitude, harmonic spectrum, source impedance, and renewable-energy generation may change continuously.

Algorithms such as Least Mean Squares, Recursive Least Squares, and related adaptive structures can estimate fundamental components and harmonic disturbances online. Adaptive filtering can therefore reduce the dependence on fixed filter parameters.

The main challenge is the balance between convergence speed, computational complexity, and steady-state accuracy. A very slow adaptive algorithm may not follow sudden load changes, whereas aggressive adaptation can increase computational requirements or introduce instability if improperly designed.

VI. REPETITIVE AND RESONANT DSP CONTROL

Power-system harmonic disturbances are generally periodic. Repetitive control exploits this characteristic by storing information about previous cycles and using it to improve future compensation. It can therefore achieve strong steady-state tracking of periodic harmonic signals.

Adaptive repetitive control can further improve performance when load conditions change. Santiprapan et al. developed an adaptive repetitive controller incorporating fuzzy logic for a three-phase four-wire APF. Their experimental investigation demonstrated improved harmonic-current tracking compared with conventional repetitive control.

The major advantage of repetitive processing is its ability to compensate periodic disturbances accurately. However, conventional repetitive controllers may respond more slowly to completely new or non-periodic disturbances. Hybrid repetitive-predictive or repetitive-adaptive architectures can therefore provide a potential solution.

VII. CURRENT TRACKING AND SWITCHING-SIGNAL GENERATION

After the reference compensation current has been generated, the APF must force the inverter current to follow it. This process is generally performed using hysteresis control, carrier-based PWM, space-vector PWM, predictive control, or other current-control methods.

Hysteresis current control is relatively simple and provides rapid response, but the switching frequency can vary. PWM-based control provides a more predictable switching frequency but requires additional modulation calculations.

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Predictive control can directly select switching states and optimize current tracking but requires greater computational resources.

Recent APF reviews emphasize that the selected current-control procedure is a major determinant of APF performance, especially for reference-current tracking and dynamic compensation.

VIII. FPGA AND REAL-TIME DSP IMPLEMENTATION

Real-time implementation is essential because APF controllers must process measurements and produce switching signals within very short sampling intervals. Digital Signal Processors, microcontrollers, Field-Programmable Gate Arrays, and real-time control platforms are therefore increasingly used.

FPGA implementation is particularly attractive for computationally demanding algorithms such as wavelet transforms, parallel filtering, predictive control, and multiple-channel signal processing. Hardware-in-the-loop research has demonstrated the use of FPGA-based computational engines for validating wavelet-controlled SAPFs with microsecond-scale computational steps.

Table 3. DSP Hardware Considerations for APF Control

Platform	Processing capability	Main advantage	Limitation
Microcontroller	Moderate	Low cost and simple implementation	Limited parallel processing
DSP processor	High	Excellent mathematical processing	More expensive than basic MCU
FPGA	Very high	Parallel processing and deterministic timing	Programming complexity
Industrial PC	Very high	Flexible and powerful	Higher cost and less compact
SoC/FPGA	Very high	Combines processor and hardware acceleration	Design complexity

IX. APPLICATION IN RENEWABLE-ENERGY AND MICROGRID SYSTEMS

The integration of renewable-energy systems creates new requirements for APF signal processing. Solar photovoltaic, wind-energy, and battery-storage converters can operate as multifunctional interfaces, simultaneously transferring active power and performing power-quality compensation.

The integration of SAPFs with renewable-energy sources has been extensively investigated because the same converter infrastructure can potentially support harmonic mitigation, reactive-power compensation, and energy management. Reviews have identified fuzzy logic, neural networks, adaptive neuro-fuzzy inference systems, and other advanced algorithms as important approaches for renewable-integrated APF control.

In PV-BESS applications, optimization-based APF functionality has also been investigated for harmonic and power-fluctuation mitigation under changing operating conditions.

X. CONCLUSION

Digital signal processing is a fundamental technology underlying modern active power filter systems. APFs provide dynamic compensation of harmonic currents, reactive power, and other power-quality disturbances, but their effectiveness depends strongly on the accuracy and speed of digital signal acquisition and processing. Fourier-based methods remain valuable for harmonic analysis, while p-q and d-q approaches provide practical reference-current generation. Digital low-pass and notch filters offer simple implementations, whereas adaptive filtering provides improved flexibility under changing load conditions. Wavelet transforms are particularly suitable for transient and non-stationary disturbances because of their time-frequency localization. Predictive control offers rapid dynamic response, while repetitive control provides effective periodic harmonic compensation. Fuzzy, neural, neuro-fuzzy, and optimization techniques further expand the possibilities for intelligent APF control.

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