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Analysis Of Active Power Filters with and without Fuzzy Logic Controllers

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Abstract

This article reviews the performance of an Active Shunt Power Filter (ASPF) operated both with and without a fuzzy logic controller. With the growing use of nonlinear loads in modern power networks, harmonic distortion has become a major concern. These harmonics generate electrical noise, weaken power quality, and affect the reliable operation of sensitive equipment.

To address this issue, the study explores methods to reduce harmonics introduced by such nonlinear loads. The review focuses on a three-phase active power filter designed to compensate harmonic currents and reactive power under both balanced and unbalanced operating conditions. Its behaviour is examined in steady-state as well as during transient events.

Keywords: Active Power; Filters; Harmonics; Fuzzy Logic Controllers.

1. Introduction

Modern power systems have seen a sharp rise in harmonic disturbances due to the extensive use of power electronic devices and energy conversion units. Power quality (PQ) has therefore become a critical parameter in evaluating the performance of electrical networks. Ideally, PQ refers to maintaining a sinusoidal current waveform that is perfectly in phase with a sinusoidal voltage waveform. While electricity produced at generating stations is purely sinusoidal, its quality often deteriorates because of current and voltage harmonics introduced by various nonlinear loads.

Equipment such as variable-speed drives, DC motors, switched-mode power supplies, electronic ballasts, and battery chargers contribute significantly to these issues. Such nonlinear devices draw non-sinusoidal currents and consume reactive power, injecting harmonic components back into the distribution network through the common coupling point. The control mechanism plays a key role in the operation of an Active Power Filter (APF), and several studies have focused on improving controller performance. Traditionally, proportional–integral (PI) controllers have been used for regulating harmonic currents and maintaining DC-link voltage in shunt APFs.

However, conventional PI controllers depend on an accurate linear model of the system, which becomes challenging under changing load conditions, parameter variations, and nonlinear behaviours. To overcome these limitations, fuzzy logic control has emerged as a promising alternative. Fuzzy controllers offer robustness, eliminate the need for precise mathematical modelling, and perform effectively in nonlinear environments.

In this work, a fuzzy logic–based control approach is applied for managing the harmonic current and DC voltage of a three-level shunt APF. The system's performance was analyzed through computer simulations under steady-state conditions. The results demonstrate that the proposed fuzzy controller significantly improves the quality of the supply current, keeping it sinusoidal and in phase with the voltage while minimizing harmonic

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distortion. A detailed explanation of the APF's operation, including harmonic current generation and inverter DC voltage control schemes, is also presented. The fuzzy control algorithm developed in this study forms the core of the system's enhanced performance.

2. Basic Active Power Filter

Figure 1 (a) shows the basic compensation principle of an active shunt power filter. It is controlled to draw or supply compensation current from or to the mains so that it cancels out the current harmonics on the AC side. Figure 2 shows the various waveforms. Curve A is the load current waveform and curve B is the desired source current. Curve C shows the compensation current or filter current injected by the active filter containing all the harmonics to make the grid current sinusoidal. Thus, an active shunt power filter can be used to eliminate the current harmonics and reactive power compensation [5].

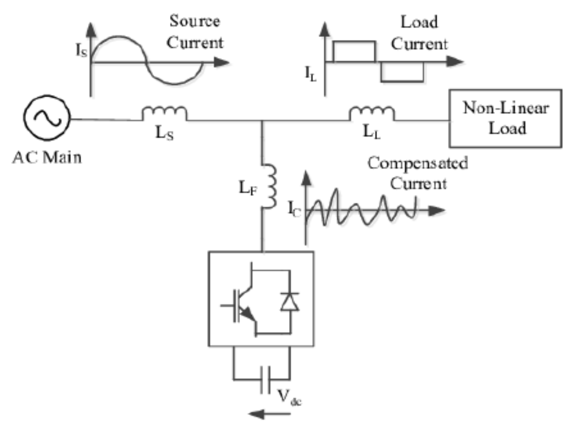

Figure 1(a) Block diagram of a Basic Active Power Filter

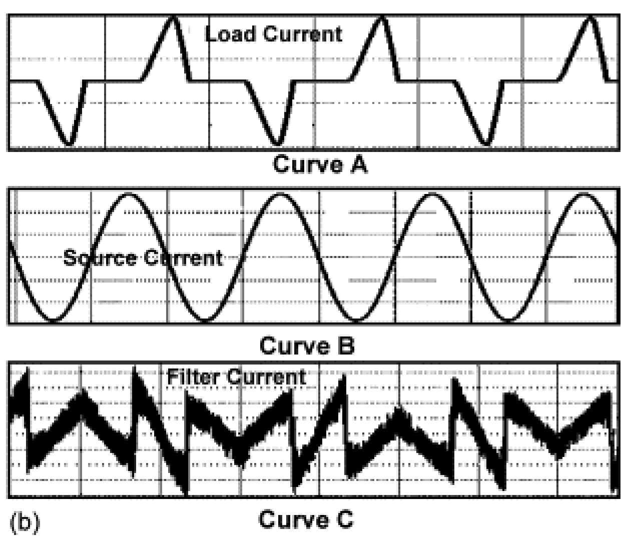

Figure 1(b) Block diagram of a basic active power filter

The instantaneous currents from Figure 1 (a)can be expressed as

$$i_s(t) = i_L(t) - i_c(t)$$

The source voltage is given by

$$v_s(t) = V_m \sin \omega t$$

If a nonlinear load is applied, the load current will have a fundamental component, and the harmonic components can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$i_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

The instantaneous charging power can be represented as

$$p_L(t) = v_s(t) * i_L(t)$$

$$p_L(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin \phi_1$$
$$+ V_m \sin \omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$
$$p_L(t) = p_f(t) + p_r(t) + p_h(t)$$

From equation (4) we get the real (fundamental) power of the load.

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\phi_1 = v_s(t) * i_s(t)$$

The current supplied by the source after compensation from equation (6)

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 \cos\phi_1 \sin \omega t = I_{sm} \sin \omega t$$

The PWM converter also has some switching losses. Consequently, the power supply must incorporate a slight surplus to compensate for capacitor drainage and converter efficiency losses, in addition to meeting the actual power demands of the load.

Therefore, the maximum total current delivered by the power source

$$I_{sp} = I_{sm} + I_{sL}$$

When the active filter supplies the entire reactive and harmonic power, the source current i_S (T) will be synchronized with the utility voltage and exhibit a pure sinusoidal waveform. Under these conditions, the active filter must generate the following compensating current.

$$i_c(t) = i_L(t) - i_s(t)$$

Therefore, to accurately and instantaneously compensate for the reactive and harmonic power, it is necessary to calculate the fundamental component (T) of the load current as the reference current.

3. Reference Source Current Estimate

The maximum value of the reference current I_{SP} can be determined by observing the voltage across the DC-side capacitor. To achieve optimal compensation, it is necessary for the primary current to be sinusoidal and aligned with the source voltage, irrespective of the load current characteristics. Following compensation, the intended source currents can be expressed as

$$i_{sa}^{*} = I_{sp} \sin \omega t,$$
$$i_{sb}^{*} = I_{sp} \sin(\omega t - 120^{o}),$$
$$i_{cb}^{*} = I_{sp} \sin(\omega t + 120^{o}),$$

Where? $I_{sp} = I_1 \cos \phi_1 + I_{sL}$ The desired source current is the amplitude and the phase angle can be obtained from the source voltage. Therefore, the waveforms and phases of the source currents are known and it is only necessary to determine the magnitudes of the source currents.

The maximum value of the reference current was estimated by regulating the voltage of the capacitor on the DC side of the PWM converter. This capacitor voltage was compared with the reference value, and the error was processed using the PI controller. The output of the PI controller is taken to be t_{Is} The amplitudes of the desired source current and reference currents are estimated by multiplying this peak value with unit sine vectors in phase with the source voltage.

3.1 DC side capacitor function

A DC-side capacitor serves two key functions:

1. it keeps the DC-link voltage steady with minimal ripple under normal operating conditions
2. it stores energy to balance temporary differences between source power and load demand during dynamic changes.

During steady-state operation, the real power supplied by the source should match the load requirement, with a small margin to cover losses in the active filter. Under these conditions, the DC-link voltage can be held close to its reference value. When the load changes, however, the power balance shifts. The DC capacitor must supply or absorb the difference, causing its voltage to rise or fall away from the reference.

To ensure proper APF operation, the peak value of the reference current is adjusted so that the source draws the required real power. The capacitor either discharges or charges to make up the mismatch between the source and the load. Once the capacitor voltage returns to its reference level, it indicates that the incoming real power matches the load's demand.

Hence, the reference source-current peak is obtained by controlling the average DC-link voltage. When the capacitor voltage is below its reference level, it signals that the source is not supplying enough power; therefore, the input current must be increased. When the voltage rises above the reference, the source current is reduced. These behaviours are confirmed through simulation.

Because real and reactive power exchange can introduce ripples on the DC-link voltage, a low-pass filter is normally used to smooth them out, though it adds delay. To avoid this delay, the DC voltage is sampled at the zero-crossing of the source voltage, enabling immediate compensation. Sampling only twice per cycle (instead of six times) slightly increases the short-term voltage rise or drop during transients, but shortens the settling time.

Harmonic mitigation is then carried out using PWM-based inverter control. By solving a set of nonlinear equations, the switching angles are selected to cancel specific harmonics while maintaining the required fundamental component. In the simulation, switching angles were determined to suppress the 5th, 7th, and 11th harmonics.

The total harmonic distortion in the inverter's output voltage and current is evaluated using a standard expression, which was applied to minimize overall distortion.

$$\%THD = \left[\frac{1}{a^2_1} \sum_{n=5}^{\infty} (a^2_n \right] \times 100$$

Then n = 6i ± 1(where, i = 1, 2, 3...)

4. Fuzzy Logic Controller

In recent decades, the use of fuzzy set theory or fuzzy logic in control systems has gained widespread popularity, particularly in Japan. Since the mid-1970s, Japanese scientists have been instrumental in translating the theory of fuzzy logic into a technical implementation. Today, control systems based on fuzzy logic, or simply fuzzy logic controllers (FLC), can be found in a growing number of products, from washing machines to speedboats, from air conditioning units to cameras, and to autofocus laptops. The inference engine is central to the operation of the fuzzy controller (and any fuzzy rule system). The actual operation can be divided into three stages.

i) Fuzzification: The real inputs are blurred, and fuzzy inputs are obtained.
ii) Fuzzy processing: Fuzzy input is processed according to established rules and fuzzy output is generated.
iii) Defuzzification: A sharp real value is generated for a fuzzy output.

5. A review

he Unified Power Quality Conditioner (UPQC) integrates both series and shunt active filters to handle a range of power-quality issues such as voltage imbalance, harmonic distortion, negative-sequence currents, and reactive power. In practical terms, a UPQC can significantly improve power quality at its point of installation in industrial or distribution networks. A control strategy based on instantaneous real and reactive power has been studied, and tests on a 20-kVA laboratory setup confirm that the approach works effectively.

Active shunt filters are commonly used to reduce current harmonics and improve power factor when nonlinear loads are present. Several control approaches exist—some rely on instantaneous reactive power theory, while others use the synchronous reference frame based on Park's transformation. The method highlighted here is intended for unbalanced systems with distorted load currents and supply voltages. It follows a time-domain principle developed by P. Filipsky. With this control strategy, the combined nonlinear load and shunt filter can behave like a simple resistive unit with unity power factor, and the overall current remains sinusoidal. Simulation results demonstrate performance under different supply and load conditions, with corresponding line-current waveforms and harmonic content.

Another approach focuses on expanding the usable capacity of shunt active filters. The technique limits reactive power and the distortion current delivered by each filter module. Under this scheme, different APFs supply full or partial rated power to match system demand. The method offers flexibility, modularity, and better tolerance to parameter mismatches. A laboratory system using three 1-kVA single-phase APFs confirms the validity of this approach.

Three commonly used methods for generating reference currents—PQ theory, synchronous reference frame (SRF), and peak detection method (PDM)—have also been compared. Their performance was evaluated under steady-state and transient conditions in a four-wire system with unbalanced single-phase nonlinear loads. Although all three methods perform similarly under ideal conditions, SRF produces the most reliable results when voltage imbalance or distortion is present.

A separate control approach using space-vector PWM has also been investigated. Instead of generating reference current, the method produces a reference voltage vector, and SVPWM is used to achieve the required output. The control logic is simple and can be implemented using a low-cost controller. A 10-kVA laboratory prototype validated its ability to remove harmonics, correct reactive power, and balance uneven loads.

A time-domain based current-detection algorithm has been proposed for three-phase shunt APFs. The method provides a clear physical interpretation and short computation delay. Because it generates compensation references accurately, it can meet different compensation goals—harmonic reduction, power-factor correction, and load balancing. Simulation and laboratory results support the method.

Multiple parallel SAPFs are gaining attention in electric ships, where high power capacity and reliability are crucial. A new parallel strategy separates reactive-power and harmonic current compensation, giving faster response and improved redundancy. Simulation results confirm the benefits.

Shunt APFs remain the most common solution for harmonic mitigation in industrial applications, especially when built using voltage-source inverters. While they suppress low-frequency harmonics, switching introduces high-frequency EMI. A random-PWM method (RPWM-II) has been proposed to spread harmonic energy over a wider frequency range, reducing EMI at little additional cost. Simulation and experimental results show strong improvement.

Recent work has also explored a synchronization technique based on Kalman-filter PLL (KF-PLL) to generate reference currents for shunt APFs. The approach was tested for harmonic cancellation, power-factor correction, and imbalance compensation, and can operate under distorted line voltages.

A simplified space-vector PWM method has been proposed, where each phase current is controlled independently. This avoids error propagation between phases and is easier to implement than conventional SVPWM. Simulation results indicate better compensation performance.

Another study addresses dead-time effects in PWM inverters, which reduce performance by distorting switching behaviour. A fast feedback control technique was introduced to compensate for these effects in shunt APFs. Both feed-forward and feedback designs were tested, with experiments showing stable and effective dead-time correction.

For four-wire systems, a nested current-control structure using a three-leg converter and a split DC-link capacitor has been analyzed. The outer loop generates reference currents, while the inner loop uses state feedback with integral action. Selective harmonic elimination and DC-capacitor-voltage control are also included. Experiments with balanced and unbalanced nonlinear loads confirm effective neutral-current and DC-voltage balancing.

Finally, a comparison of resonant and predictive controllers for shunt APFs highlights how current-control strategy influences performance. Both approaches were evaluated under similar conditions. Their dynamic response, steady-state accuracy, and sensitivity to supply-impedance variations were compared through simulation.

6. Conclusion

Energy transmission and distribution networks are increasingly vulnerable to harmonic distortion due to the widespread use of power electronic equipment. This problem has drawn significant attention from power-system and automation researchers, leading to the development of various mitigation methods. One effective approach is the use of active shunt filters for harmonic compensation.

This work outlines the operation of the power system, inverter circuit, and harmonic behaviour of a three-phase active shunt filter. Harmonic reduction is confirmed through total harmonic distortion (THD) measurements and circuit simulation. In a four-wire setup, where the neutral conductor is connected to the midpoint of the DC-link capacitor, the shunt filter is capable of compensating both balanced and unbalanced nonlinear load currents.

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