

Power Quality Enhancement Using a Fuzzy Logic-Based Shunt Active Power Filter with Instantaneous Power Theory

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Abstract: The rapid growth of power electronic converters and other nonlinear loads has made current harmonics, poor power factor and reactive power burden the dominant power quality problems in modern distribution networks. This paper presents a three-phase shunt active power filter (SAPF) in which the reference compensating currents are extracted using the instantaneous reactive power ($p-q$) theory and the DC-link capacitor voltage is regulated by a Mamdani-type fuzzy logic controller (FLC) in place of the conventional proportional-integral (PI) controller. The fuzzy controller uses the DC-link voltage error and its change as inputs, with seven linguistic sets per variable and a 7×7 rule base of 49 rules. A hysteresis current controller generates the gating pulses of the IGBT-based voltage source inverter. The complete system, supplying a three-phase diode bridge rectifier load from a 50 Hz grid, is modelled in MATLAB/Simulink. The total harmonic distortion (THD) of the source current falls from 25.80% without compensation to 4.64% with the PI-controlled SAPF and to 1.45% with the fuzzy-controlled SAPF, well within the IEEE 519 limit of 5%. The fuzzy controller also settles the DC-link voltage at its 740 V reference without overshoot, whereas the PI controller leaves a steady offset of about 5 V.

Keywords: Active power filter, fuzzy logic controller, harmonics, hysteresis current control, instantaneous power theory, $p-q$ theory, power quality, total harmonic distortion

I. INTRODUCTION

Nonlinear loads such as electronic lighting, rectifiers, adjustable speed drives and switched-mode power supplies now form a large share of the electrical load, and they draw non-sinusoidal currents from the supply [1], [2]. Grid-connected converters for solar and wind generation add further distortion through their PWM switching [3]. The resulting current harmonics distort the voltage at the point of common coupling (PCC), increase losses, overheat transformers and neutral conductors, cause nuisance tripping and metering errors, and interfere with communication circuits. Such harmonics are harmful to the electrical system and must be suppressed [4]. IEEE 519 therefore limits the total harmonic distortion (THD) of the current drawn at the PCC to 5%.

Passive LC filters have traditionally been used to suppress harmonics and supply reactive power. They are simple and cheap, but their compensation is fixed, they are bulky, they are tuned to particular harmonic orders and they can resonate with the source impedance [5], [6]. Active power filters (APFs) overcome these drawbacks: a power electronic converter injects a compensating current or voltage that cancels the harmonic content of the load and adapts automatically to load changes [6], [7]. APFs are classified as shunt, series and hybrid filters [7], [8]. The shunt active power filter (SAPF) is connected in parallel with the load at the PCC and injects a current equal in magnitude and opposite in phase to the harmonic and reactive components of the load current, so that the source supplies only a sinusoidal current in phase with the voltage [8], [9].



An SAPF depends on three control tasks: extraction of the reference compensating current, regulation of the DC-link capacitor voltage, and generation of the switching signals that make the inverter track the reference [8]. Time-domain methods such as the instantaneous reactive power (p-q) theory and the synchronous reference frame (d-q) theory are preferred for reference extraction because they act instantaneously and avoid the delay of FFT-based methods [5]. For the inner current loop, hysteresis current control is widely used because it is simple, robust and fast [6]. Recent work has refined this loop further. Hajje et al. [1] proposed fuzzy and modulated hysteresis current controllers for a three-phase four-wire split-capacitor SAPF supplying compact fluorescent lamps and, on a Typhoon HIL-402 platform, reduced the source current THD to 1.08% without notches near the zero crossings. Abdel-Aziz et al. [2] applied model predictive current control to a low-cost four-switch SAPF with only two interface inductors and, in simulation and experiment, reported a 20% reduction compared with a conventional hysteresis band current controller, and Mohiuddin et al. [3] showed that a sector-based space vector PWM pattern lowers harmonic distortion and switching losses in grid converters. Reduced-switch, transformerless SAPF topologies have also been proposed to lower cost [9].

The DC-link voltage loop is conventionally closed with a PI controller. A PI controller is tuned around one operating point using a linear model, so its response deteriorates under parameter variation, nonlinear operation and sudden load changes. Intelligent controllers need no accurate model and give lower harmonic content than conventional controllers [4]. Sahu [10] designed an ANFIS-controlled shunt active filter with SPWM switching. Biricik et al. [11] proposed a hybrid active power filter, combining power capacitors and LC filters with a shunt APF and a self-tuning filter algorithm, that works under distorted grid voltages. Martinek et al. [12] used ANFIS to estimate the compensating current of a shunt APF and obtained a fast dynamic response. Shah [13] used a fuzzy controller to generate the reference currents and regulate the DC capacitor voltage of a shunt filter. Acuna et al. [14] applied model predictive control to a four-leg VSI-based shunt APF to compensate current harmonics and neutral current. Kumar et al. [15] found that a fuzzy-controlled SAPF outperforms a PI-controlled one for balanced, unbalanced and variable loads.

This paper combines the p-q theory for reference current generation with a Mamdani fuzzy logic controller for DC-link voltage regulation in a three-phase SAPF supplying a diode bridge rectifier load. The main contributions are: (i) a 7×7 , 49-rule fuzzy controller that replaces the PI controller in the DC-link loop of a p-q theory based SAPF; (ii) a complete MATLAB/Simulink model including the hysteresis current controller and the IGBT inverter; and (iii) a comparison of the fuzzy and PI controlled filters in terms of source current THD and DC-link voltage regulation. Section II describes the system, Section III the p-q theory, Section IV the fuzzy controller, Section V the results, and Section VI concludes the paper.

II. SYSTEM CONFIGURATION

The studied system is a three-phase, three-wire, 50 Hz supply feeding a nonlinear load, with the SAPF connected in shunt at the PCC (Fig. 1). The nonlinear load is a three-phase uncontrolled diode bridge rectifier with an RL load on its DC side. It draws a quasi-square current of about 9.5 A peak, rich in the 5th, 7th, 11th and 13th harmonics.

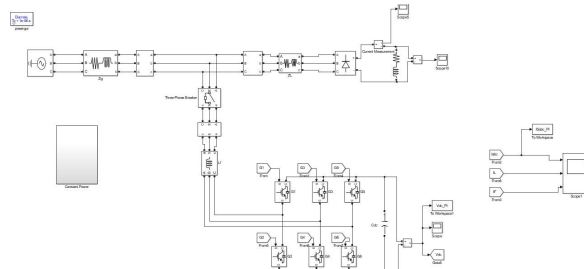


Fig. 1. Grid system with nonlinear load and shunt active power filter connected at the PCC.

The SAPF is a two-level, six-switch IGBT voltage source inverter (VSI) with a DC-link capacitor, connected to the PCC through interface inductors L_f . The filter must inject a current i_f such that the source current is sinusoidal:

$$i_s(t) = i_L(t) - i_f(t) \quad (1)$$



$$i_f(t) = i_{Lh}(t) + i_{Lq}(t) \quad (2)$$

where i_s , i_L and i_f are the source, load and filter currents, and i_{Lh} and i_{Lq} are the harmonic and fundamental reactive components of the load current. The source then supplies only the fundamental active current plus a small current that covers the inverter losses and keeps the capacitor charged.

The control scheme has three parts. The p-q theory calculates the reference compensating currents from the PCC voltages and load currents. The DC-link voltage controller (PI or fuzzy) compares the capacitor voltage with its 740 V reference and produces the loss power p_{loss} . A hysteresis current controller then generates the gate pulses for the six IGBTs. Table I lists the main parameters.

TABLE I. SYSTEM PARAMETERS

Parameter	Value
Supply	Three-phase, three-wire, 50 Hz [line voltage to be added]
Nonlinear load	Diode bridge rectifier with RL load [R, L to be added]
Filter	Two-level, six-switch IGBT VSI
DC-link reference voltage	740 V
Interface inductance / DC-link capacitance	[to be added]
Reference current extraction	p-q theory
DC-link controller	PI / Mamdani fuzzy (49 rules)
Current controller	Hysteresis
Filter connected / simulation time	0.2 s / 0.5 s

III. INSTANTANEOUS POWER (P-Q) THEORY

The p-q theory defines instantaneous real and imaginary powers in a stationary orthogonal frame and separates the load power into constant and oscillating parts in the time domain [5], [8]. It is valid in both steady state and transients and needs no FFT.

A. Clarke Transformation

The PCC voltages and load currents are transformed from the a-b-c frame to the stationary α - β frame. In a three-wire system the zero-sequence components are absent, so only the α and β rows are retained:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (4)$$

B. Instantaneous Real and Imaginary Powers

The instantaneous real power p and imaginary power q of the load are

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

Each contains an average part produced by the fundamental positive-sequence current and an oscillating part produced by the harmonics:

$$p = \bar{p} + \tilde{p}, \quad q = \bar{q} + \tilde{q} \quad (6)$$

The average real power $\bar{p}$ is the only component the source should supply. The filter therefore compensates $\tilde{p}$ and the whole of $\tilde{q}$:

$$p_c^* = \tilde{p} - p_{loss}, \quad q_c^* = \tilde{q} \quad (7)$$



where p_{loss} , the output of the DC-link voltage controller, is the active power the inverter must draw from the grid to cover its losses and hold the capacitor voltage at the reference.

C. Reference Current Generation

The reference currents in the α - β frame are

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} v_{\alpha} & v_{\beta} \\ v_{\beta} & -v_{\alpha} \end{bmatrix} \begin{bmatrix} p_c^* \\ q_c^* \end{bmatrix} \quad (8)$$

and the three-phase references follow from the inverse Clarke transformation:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \quad (9)$$

Fig. 2 shows the Simulink implementation of this control structure with the fuzzy DC-link controller.

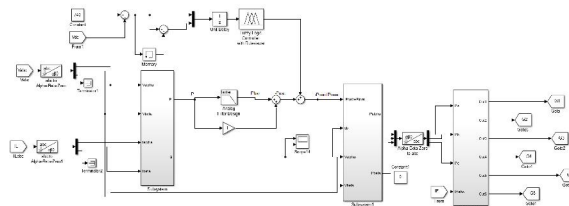


Fig. 2. p-q theory control structure of the SAPF with the fuzzy DC-link voltage controller.

D. Hysteresis Current Control

The hysteresis controller compares each reference current with the measured filter current of the same phase (Fig. 3). When the error exceeds the upper limit ($i^* + h/2$), the lower switch of that leg is turned on to reduce the current; when it falls below the lower limit ($i^* - h/2$), the upper switch is turned on. The current thus stays within a band of width h around the reference [1], [6]. The method is simple, independent of load parameters and very fast; its drawback is a variable switching frequency.

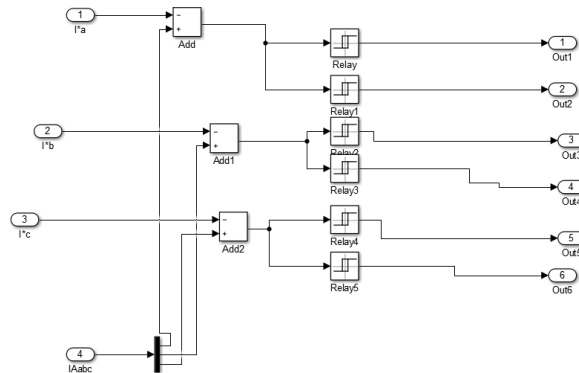


Fig. 3. Hysteresis current controller for generation of gate pulses.

IV. FUZZY LOGIC BASED DC-LINK VOLTAGE CONTROLLER

A. Need for an Intelligent DC-Link Controller

The DC-link capacitor is the energy buffer of the SAPF; its voltage must stay at the reference so that the inverter can always force the required current into the PCC. In the conventional scheme a PI controller acts on the error



$$e(k) = V_{dc}^* - V_{dc}(k) \quad (10)$$

to produce p_{loss} . With fixed gains tuned on a linearised model, the response is a compromise between speed, overshoot and steady-state accuracy [4], [15]. A fuzzy controller instead encodes the correction strategy as linguistic rules, needs no plant model, and adapts its effective gain to the size and trend of the error [10], [13].

B. Structure of the Fuzzy Controller

The Mamdani controller (Fig. 4) has four parts: fuzzification, rule base, inference engine and defuzzification. Its inputs are the error $e(k)$ and the change of error

$$\Delta e(k) = e(k) - e(k-1) \quad (11)$$

and its output is p_{loss} .

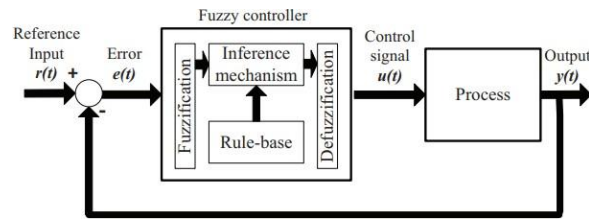


Fig. 4. Block diagram of the fuzzy logic controller.

Fuzzification: Each variable has seven linguistic sets: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). Triangular membership functions with 50% overlap are spaced evenly over the normalised range $[-1, 1]$ (Fig. 5).

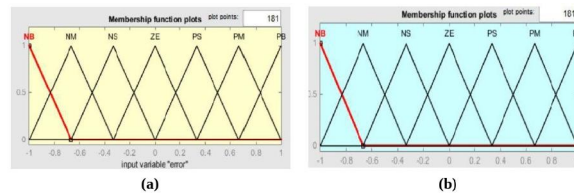


Fig. 5. Membership functions: (a) input variable (error), (b) output variable.

Rule base and inference: The 49 rules, of the form IF e is A_i AND Δe is B_j THEN p_{loss} is C_{ij} , were set in the MATLAB Fuzzy Logic Toolbox and are listed in Table II. When the voltage is far below the reference and still falling (e and Δe both PB), the controller demands a large positive p_{loss} so that the inverter draws more power from the grid. When the error is small and decreasing, the output is reduced to avoid overshoot, and when the error is zero and steady the output is held at ZE. The rules are combined with Mamdani inference using the AND connective.

TABLE II. FUZZY RULE BASE (ROWS: e , COLUMNS: Δe)

$e \Delta e$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Defuzzification: The aggregated fuzzy output, expressed in linguistic terms, is converted into the crisp value of p_{loss} that is passed to the p-q controller.



V. SIMULATION RESULTS AND DISCUSSION

The fuzzy-controlled SAPF reduces the source current THD from 25.80% to 1.45%, against 4.64% for the PI-controlled SAPF. The system of Fig. 1 was simulated for 0.5 s. The SAPF is disconnected from 0 to 0.2 s, so the uncompensated behaviour of the load can be observed, and is connected at $t = 0.2$ s. Two cases were studied with the same p-q reference extraction and hysteresis current controller: (a) a PI and (b) the proposed fuzzy controller in the DC-link loop.

A. Source, Load and Compensating Currents

Fig. 6 shows the source, load and compensating currents. Before $t = 0.2$ s the source current equals the load current: a quasi-square waveform of about 9.5 A peak with sharp steps at each diode commutation. When the filter is connected at $t = 0.2$ s, a short transient follows, with a first peak of about 30 A while the compensating current builds up. Within about 1.5 cycles ($t \approx 0.23$ s) the source current becomes sinusoidal with a peak of about 10 A. The load current is unchanged, and the compensating current, of about 5 A peak, carries the harmonic content of the load.

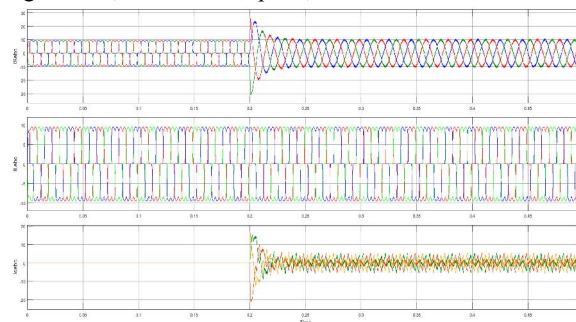


Fig. 6. Source currents (top), load currents (middle) and compensating currents (bottom); SAPF connected at $t = 0.2$ s.

B. DC-Link Voltage Regulation

Fig. 7 compares the DC-link voltage with the two controllers. Before connection the capacitor voltage is about 700 V and decays slowly. After $t = 0.2$ s both controllers charge the capacitor towards the 740 V reference within about 0.05 s. The PI-controlled voltage overshoots to about 746 V and stays about 5 V above the reference until the end of the simulation. The fuzzy-controlled voltage rises without overshoot and settles at 740 V by $t \approx 0.25$ s with a small ripple. This accurate regulation lets the inverter track the reference current more closely and is the main reason for the lower THD with the fuzzy controller.

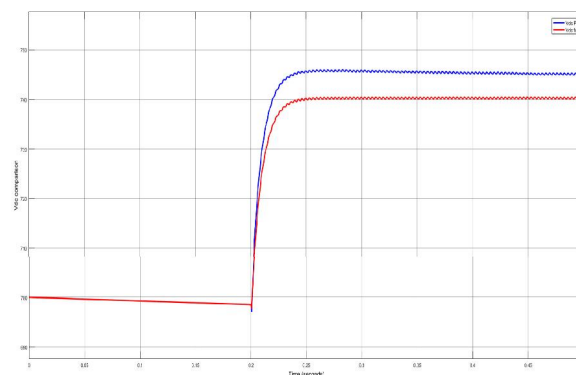


Fig. 7. DC-link capacitor voltage with PI (blue) and fuzzy (red) controllers.



C. Harmonic Analysis

The THD of the source current was computed with the powergui FFT tool over three cycles of the 50 Hz fundamental, starting at $t = 0.1$ s for the uncompensated case and $t = 0.4$ s for the compensated cases, with the THD evaluated up to the Nyquist frequency:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100\% \quad (12)$$

where I_1 and I_h are the magnitudes of the fundamental and the h -th harmonic. Fig. 8 shows the spectra and Table III summarises the results.

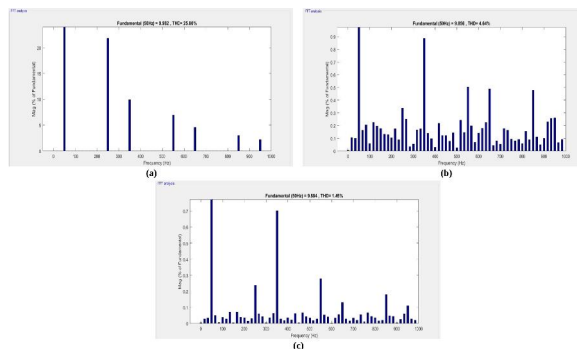


Fig. 8. FFT spectrum of source current: (a) without SAPF, THD = 25.80%; (b) with PI-controlled SAPF, THD = 4.64%; (c) with fuzzy-controlled SAPF, THD = 1.45%.

TABLE III. THD OF SOURCE CURRENT

Case	THD (%)	IEEE 519 (5%)
Without SAPF	25.80	Not met
SAPF, p-q + PI	4.64	Met
SAPF, p-q + fuzzy	1.45	Met

Without the filter, the 5th harmonic is about 22% of the fundamental, the 7th about 10%, the 11th about 7% and the 13th about 4.6%, giving a THD of 25.80%. With the PI-controlled SAPF the THD falls to 4.64%, which meets the IEEE 519 limit with little margin. With the fuzzy-controlled SAPF it falls to 1.45%, and every individual harmonic is below 0.8% of the fundamental. This is a 94.4% reduction relative to the uncompensated case and a 68.8% reduction relative to the PI-controlled filter. The fundamental amplitude stays nearly constant at about 9.9 A in all three cases. The result is comparable to the 1.08% reported by Hajje et al. [1] with advanced hysteresis current controllers, although the present work keeps the conventional hysteresis loop and improves only the DC-link loop, so the two approaches could be combined.

VI. CONCLUSION

A three-phase shunt active power filter using the p-q theory for reference current extraction and a Mamdani fuzzy logic controller for DC-link voltage regulation has been presented and simulated in MATLAB/Simulink. Connected at the PCC of a 50 Hz grid feeding a diode bridge rectifier load, the filter injects the harmonic and reactive components of the load current through a hysteresis-controlled IGBT inverter, and the source current becomes sinusoidal within about 1.5 cycles. The 49-rule fuzzy controller settles the DC-link voltage at its 740 V reference without overshoot, whereas the PI controller leaves an offset of about 5 V. The source current THD falls from 25.80% without compensation to 4.64% with the PI-controlled SAPF and to 1.45% with the fuzzy-controlled SAPF, well within the 5% limit of IEEE 519.



In future work, adaptive control and optimisation techniques can be applied to the fuzzy controller to stabilise the DC-link voltage faster, and to reduce the peak current drawn when the filter is connected. Other soft-computing controllers can also be developed and examined for the same filter.

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