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A fuzzy logic approach to shunt active power filter and hybrid active power filter

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Abstract

This paper describes a fuzzy logic approach to shunt active power filter (SAPF) versus hybrid active power filter (HAPF) using Simulink. Here hysteresis controlled PWM method is applied to the SAPF and HAPF as a current controller and fuzzy logic controller as an inverter DC voltage controller. To reduce harmonics, shunt active power filters (SAPFs) are used with various control schemes, but hybrid active power filter is a power electronic device which has both the characteristics of passive power filters and active power filters, which helps in cancelation of the harmonics by producing compensating signal. The fuzzy-hysteresis controller is designed, and its simulation results are presented for both the filter types, showing acceptable THD results for the word length used in the fixed-point computations involved in the switching sequence generation. The results of the above controller are compared with the indirect current controller.

Keywords: Index terms – shunt active power filter (SAPF), hybrid active power filter (HAPF), hysteresis current controller (HCC) and total harmonic distortion (THD), indirect current controller.

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1. Introduction

Nowadays, the harmonic current flowing into the grid leads to degradation in power quality. Economic activities depend on electrical energy quality and efficiency. Harmonics are the major problems associated with these nonlinear loads. Many researchers have been working for the elimination of harmonics in power systems due to nonlinear loads [1].

Continuous use of nonlinear loads like variable switching devices produces harmonics to power system that degrades the power quality. The harmonic results in equipment overheating, data losses, power losses, malfunctioning of the grid components. Elimination of harmonics due to the nonlinear loads passive power filters (PPF) with some merits like reliable operation, easy design procedure, act as reactive power compensators, but has many disadvantages such as large numbers of components, bulky in nature, depend on system impedance, tuned for a certain loading condition. By overcoming these disadvantages of PPF, nowadays active power filter (APF) has an effective role in harmonic elimination. The shunt APF based on voltage source inverter (VSI) structure is an attractive solution to harmonic current problems. The shunt active filter is a pulse width modulated (PWM) voltage source inverter (VSI) that is connected in parallel with the load. It has the capability to inject harmonic current into the AC system with the same amplitude but opposite phase than that of the load. The principal components of the APF are the VSI, a DC energy storage device that in this case is a capacitor and the associated control circuits [2-3].

The main purpose of the shunt APF system is to supply the harmonics absorbed by the nonlinear load, in order to provide the grid current with a low-harmonic content. To this end, the control of APF systems has been widely studied in the literature. The basic approach consists of two control loops. The outer voltage loop is responsible for capacitor-voltage regulation while the inner current loop performs the reference current-signal tracking. For the reference-signal generation, the direct method consists of sensing the load current and extracting the harmonic content. Then, the filter current is used in the inner current loop in order to track the load current harmonics [4-5]. As an alternative, the indirect method generates a sinusoidal reference signal by means of grid-voltage sensing. In that case, the grid current is forced to follow this sinusoidal signal, and thus, the load harmonics are indirectly given by the APF inductor current [6-9].

In order to improve the performance of the inner current loop, optimal, neural, and model reference adaptive controls have been used recently [10-12]. Other approaches utilize nonlinear regulators, such as sliding-mode control and hysteretic control [13-14]. All the previously mentioned controls attenuate the current harmonics only to a certain level. Repetitive control has been used in the past to implement suitable selective harmonic compensators [15-16]. This type of control includes the internal model in the closed-loop system to assure low error in steady state.

Recently, the use of fuzzy logic controllers (FLC) has been increased rapidly in power systems, such as in load-frequency control, bus bar voltage regulation, stability, load estimation, power flow analysis, parameter estimation, protection systems, and many other fields. The advantages of FLC's over the conventional controllers are: (i) It does not need accurate mathematical model (ii) It can work with imprecise inputs (iii) It can handle non-linearity(iv)It is more robust than conventional non-linear controllers.

This paper explores the potential and feasibility of fuzzy logic control schemes that are suitable for harmonic current mitigation and inverter DC voltage control to improve the performances of the shunt SAPF and HAPF. The performance of fuzzy controller is evaluated through computer simulation. The results show that the proposed active filter with fuzzy logic controller is capable of providing sinusoidal source current(s) with low harmonic distortion and the current is in phase with the corresponding line voltage. The operation of APF is demonstrated in detail. The method of extracting reference current(s) and DC capacitor voltage is also presented [17-18]. Utilization of fast switching transistors (i.e., IGBT) in APF application causes switching frequency noise to appear in the compensated source current. This switching frequency noise requires additional filtering to prevent interference with other sensitive equipment. These technical limitations of conventional APFs mentioned above can be overcome with hybrid APF configurations. They are typically the combination of basic APFs and passive filters. Hybrid APFs, inheriting the advantages of both passive filters and APFs provide improved performance and cost-effective solutions [19-21]. The concept is validated through extensive simulation. This paper is organized as follows. Section II describes the active power filter topology. Section III presents the design of the proposed control. Section IV verifies the expected features of the proposed controller by means of simulation results. In addition, a performance comparison with both a basic indirect current controller and the PI controller is provided. Section V presents the conclusions of this paper.

2 Active power filter topology

Figure **Error! Reference source not found.** shows the schematic diagram of a single-phase shunt APF connected to a distribution network. Figure **Error! Reference source not found.** shows the schematic diagram of a single-phase hybrid APF connected to a distribution network. The idea behind the present scheme is to simultaneously reduce the switching noise and electromagnetic interference. Although SAPF is able to absorb the harmonics from nonlinear loads, HAPF shows better performance. In HAPF the harmonic's filtering task is divided between the two filters. The SAPF cancels the lower order harmonics, while the HAPF filters the higher order harmonics. The main objective of HAPF is to improve the filtering performance of higher-order harmonics while providing a cost-effective lower-order harmonics mitigation. Passive filters act as the least impedance path to the tuned harmonic frequencies which are used initially to reduce harmonics. Active filters overcome drawbacks of passive filter by using the switched mode power converter to perform complete harmonic current elimination. As a result, the HAPF performs the best for harmonic elimination.

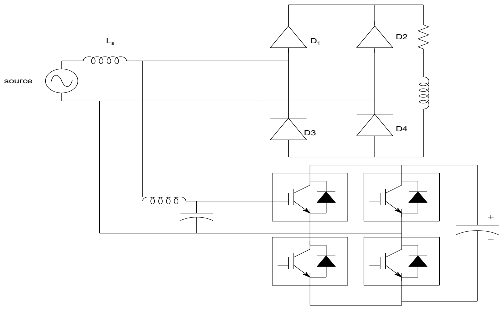


Figure 1: Diagram of shunt active power filter

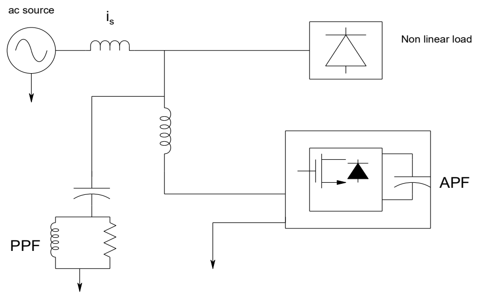


Figure 2: Diagram of hybrid active power filter

3 Control strategy

A. Reference source current generation

In order to determine harmonic and reactive components of load current, reference source current generation is needed. Thus, reference filter current can be obtained when it is subtracted from total load current. For better filter performance, generation of reference source current should be done properly. For this purpose, several methods such as pq-theory [22-25], dq-transformation [26], multiplication with sine function [27-28] and Fourier transform [29] have been introduced in literature. In this paper multiplication with sine function method is used for extraction of reference source current. This method requires much less computation time compared to the other methods. It can also provide a response time of half cycle for load containing odd harmonics only. In this method it is assumed that after compensation the source current I_{ac}will become sinusoidal in phase with voltage V_{ac}.Then instantaneous power drawn by load is calculated as in (3).

$$V_{ac}(t) = V_m \sin(\omega t) \tag{1}$$

$$I_{ac}(t) = I_m \sin(\omega t) \tag{2}$$

$$P_L(t) = V_{ac}(t) I_{ac}(t) = V_m I_m sin^2(\omega t) \tag{3}$$

Average of equation (3) given over one cycle gives the active power drawn by the load as in equation (4) and (5).

$$P_L = \frac{1}{2\pi}\int_0^{2\pi} V_m I_m sin^2(\omega t)(d\omega t) \tag{4}$$

$$P_L = \frac{V_m I_m}{2} \tag{5}$$

Therefore, if the active power of the load before and after compensation are analyzed, peak values of reference source current can be calculated.

$$I_m^* = \frac{2P_L}{V_m} \tag{6}$$

After multiplication of peak values of reference source current with unity sine function, reference source current can be obtained.

$$I_{ac}^*(t) = I_m^* \sin(\omega t) = \frac{2P_L}{V_m}\sin(\omega t) \tag{7}$$

And finally reference filter current can be obtained by subtracting load current from the reference source current as given in equation (8).

$$I_f^*(t) = I_{ac}^*(t) - I_{ld}^*(t) \tag{8}$$

B. Fuzzy logic-based DC bus voltage controller

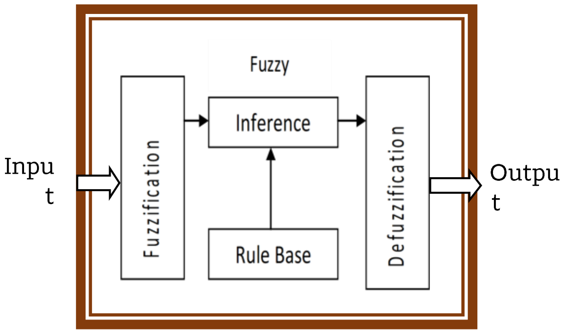


Figure 3: Fuzzy logic controller

The concept of fuzzy logic (FL) was proven to be an excellent choice for many control system applications since it mimics human control logic [30]-[35]. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Therefore, limitation or boundaries of fuzzy sets are undefined and ambiguous and useful for approximate systems design. In order to implement the fuzzy logic control algorithm of an active power filter in a closed loop, the DC-bus capacitor voltage is sensed and then compared with the reference value. The compared error signal ($e(t) = V_{dcref} - V_{dc}$) allows only the fundamental component using the filters. Firstly, the error e(t) and the variation error de(t) have been placed in the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control voltage u(t). The output of the fuzzy logic controller limits the magnitude of peak reference current, which is the command signal to the PWM of the filter inverter. The input uses Gaussian membership functions while the output uses triangle membership function. The block diagram of fuzzy logic controller is shown in Figure Figure 3. The FLC mainly consists of three processes:

- Fuzzification
- Inference
- Defuzzification
- Rule base.

*1) **Fuzzification:*** Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error between reference signal and output signal can be assigned as (NB, NS, Z, PS, PB) which mean big, negative small, zero, positive small and positive big respectively. The process of fuzzification includes numerical variable (real number) conversion to a linguistic variable (fuzzy number).

2) Inference: The behaviour of the control surface which relates the input and output variables of the system is governed by a set of rules. A typical rule would be $I_f x$ is A then y is B.

When a set of input variables are read each of the rule that has any degree of truth in its premise is fired and contributes to the forming of the control surface by approximately modifying it. When all the rules are fired, the resulting control surface is expressed as a fuzzy set to represent the constraints output. This process is termed as inference.

*3) **Defuzzification:*** The rule of fuzzy logic generation requires output in a linguistic variable, according to real world requirements; linguistic variables have to be transformed to crisp output (real number). This selection of strategy is compromised between accuracy and computational intensity. Defuzzification uses the height method.

4) Rule base*:* The rule base stores the linguistic control rules required by rule evaluator (decision making logic). The output of the fuzzy controller estimates the magnitude of peak reference current. The current takes response of the active power demand of the non-linear load for harmonics and reactive power compensation.

Table 1: Fuzzy inference rules [36]

u(t)	***e(t)***					
		NB	NS	Z	PS	PB
de(t)	NB	NB	NB	NS	NS	Z
	NS	NB	NS	NS	Z	PS
	Z	NS	NS	Z	PS	PS
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PS	PB	PB

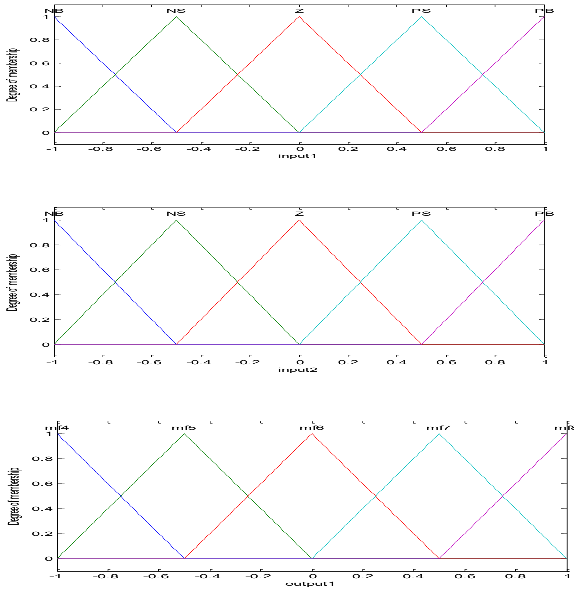


Figure 4: Membership functions of input variables for fuzzy logic controller

A. Hysteresis band current controller

Hysteresis band current controller forces the filter current to follow derived reference current. In this paper, hysteresis band current control method is used because implementation of this control is not expensive, and the dynamic answer is excellent

Figure Figure 5 shows the two levels hysteresis current control indicating the upper hysteresis band, lower hysteresis band, actual and reference current. Conventional HCC operates the PWM voltage source inverter by comparing the current error against fixed hysteresis bands. The difference between the reference current and the current being injected by inverter means the current error. When this current error exceeds the upper limit of the hysteresis band the lower switch of the inverter arm is turned on and the upper switch is turned off and vice versa. In this manner it reduces the current error.

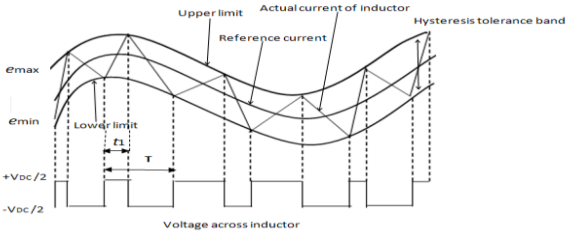


Figure 5: Diagram of hysteresis band

4 Results and analysis

The simulation results of the proposed shunt active power filter and hybrid active power filter controlled by fuzzy logic are presented. The THD results of both fuzzy hysteresis controller and indirect current controller with PI are also compared. The parameters of Kp and Ki are derived from the formula given below [37]. The output of PI controller is:

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{9}$$

where $e(t) = V_{dcref} - V_{dc}$

$$K_p = 2\zeta \sqrt{\frac{T}{T_i}} - 1 \tag{10}$$

$$K_i = \frac{K_p}{T_i} \tag{11}$$

We used Simulink toolbox in the MATLAB software in order to model and test the system under steady state and transient conditions. The Table Table 2 represents steady state system parameters of active power line conditioners with non-linear load.

Table 2: Steady state system parameters

Load inductance Load resistance	10.02e-3 H ,3 OHM
Line resistance Inductance	0.001 OHM, 10.01e-3H
Filter resistance inductance	3.8-ohm, 89.098 H
Dc capacitor	1000 uF
V ref	300 v
Source voltage	120 v, 50 Hz
Kp, Ki	0.3,10

Passive filter inductance and capacitance	100 mH, 100 uF
Delay time	2e-6sec
APF DC link voltage reference	300 V
Hysteresis band limit	0.5 Amp

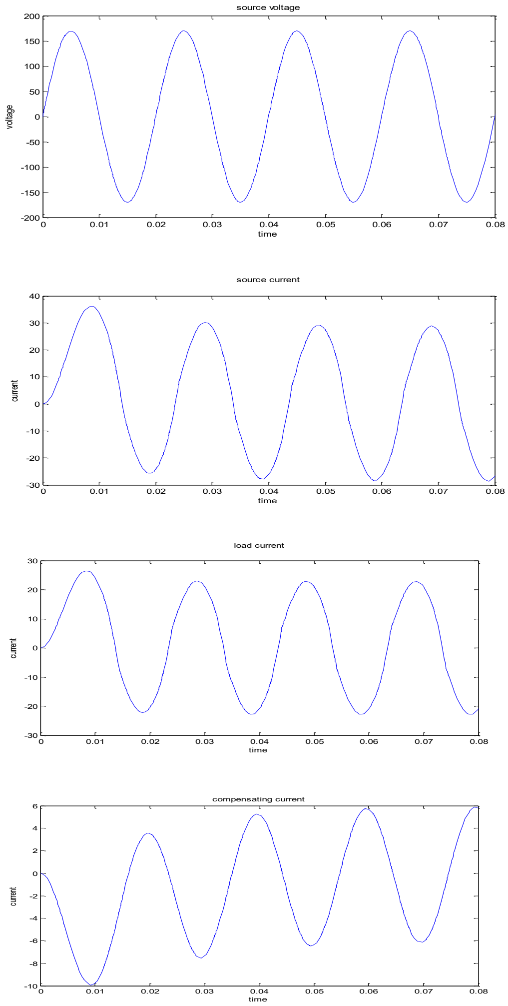
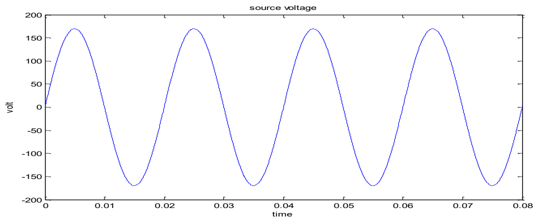


Figure 6: Shunt APF source voltage, source current, load current and compensating current with FLC



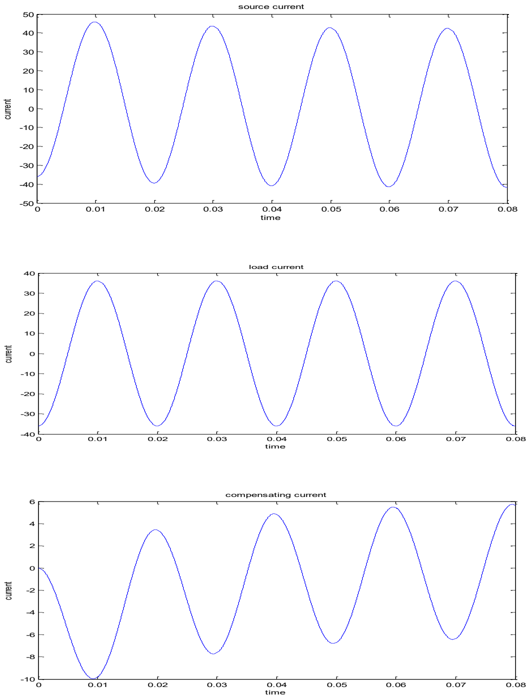


Figure 7: Hybrid APF source voltage, source current, load current and compensating current with FLC

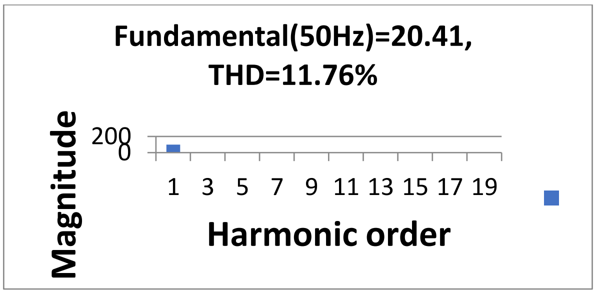


Figure 8: FFT analysis of source current indirect current controlled shunt APF(THD=11.76%)

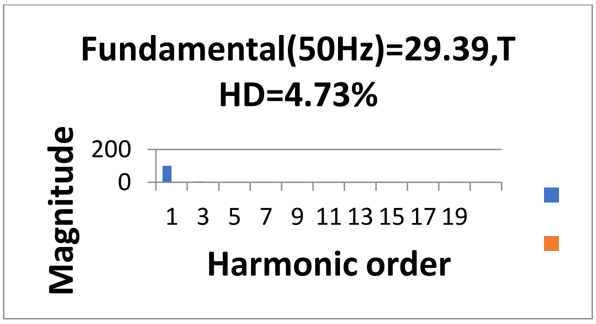


Figure 9: FFT analysis of source current shunt APF(THD=4.73%)

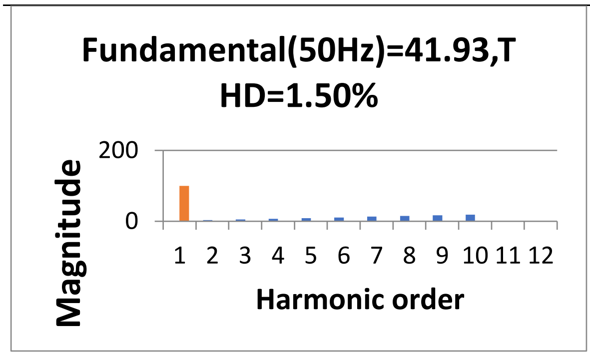


Figure 10: FFT analysis of source current hybrid APF (THD=1.50%)

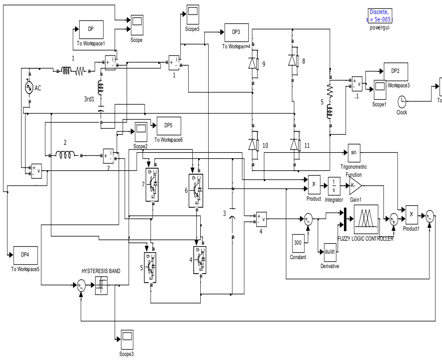


Figure 11: Simulink model APF with fuzzy logic controller

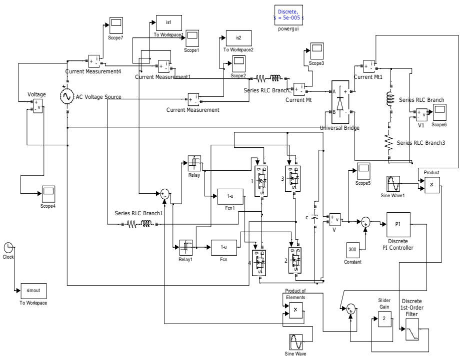


Figure 12: Simulink model APF with indirect current controller

Table 3: Harmonic content of input current

	Voltage Control Technique	Current Control Technique	THD (%)	Individual harmonic content (% of fundamental) of input current								
				3	5	7	9	11	13	15	17	19
Shunt APF	Fuzzy	Hysteresis	4.73	4.24	1.84	.81	.40	.31	.24	.17	.13	.11
	PI	Indirect	11.6	2.18	3.45	3.04	1.09	1.44	1.22	.94	.71	.69
Hybrid APF	Fuzzy	Hysteresis	1.50	.62	.37	.26	.24	.17	.14	.12	.11	.10
	PI	Indirect	3.6	.1	1.5	1.4	.15	1.7	1.4	.15	1.4	1

5 CONCLUSION

This paper has presented a fuzzy- hysteresis based current control technique for shunt active filter and hybrid active power filter. The THD result is compared with indirect current controlled technique and PI voltage-controlled technique. The simulation results for both the models show the THD reduced to 4.73% for fuzzy hysteresis controller from 11.76% which is obtained by indirect PI controller in SAPF. The HAPF shows better performance in comparison to SAPF and THD reduced to 1.5% for fuzzy hysteresis and 3.6% for indirect PI controller. For comparison, the system was simulated with the same parameters. Therefore, HAPF is effective and economic for solving harmonic problems. The active filter was simulated using MATLAB/ Simulink and the performance was analyzed in a sample power system with a source and a non-linear load. The fuzzy-hysteresis control has quick response time, and it keeps the switching frequency nearly constant with good quality of filtering for HAPF. The simulation results show the efficiency of the fuzzy logic controller in maintaining the DC voltage set point.

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