Variable Hysteresis Band Current Controller of Shunt Active Filter Based Fuzzy logic Theory under Constant Switching Frequency

M.B.B. Sharifian, R. Rahnavard, Y. Ebrahimi

Abstract— **Hysteresis current control is one of the simplest techniques used to control the magnitude and phase angle of three phase shunt active filter injection currents for high speed compensation systems, primarily because of its simplicity of implementation, fast current control response, and inherent peak current limiting capability. However conventional fixed-hysteresis band control has a variable switching frequency throughout the fundamental period, and consequently the load current harmonic ripple is not optimum. Among the various adaptive hysteresis band techniques, analytical method is a regular and simple for solving misrules of fixed hysteresis band. But it requires good knowledge of the load parameters. This paper describes the application of fuzzy logic theory to the three-phase shunt active power filter for the power-quality improvement and reactive power compensation required by a nonlinear load under constant switching frequency. The advantage of fuzzy logic control is that it does not require a mathematical model of the system. Fuzzy hysteresis band techniques are employed to derive the switching signals. The novel adaptive hysteresis band current controller changes the hysteresis bandwidth according to modulation frequency, supply voltage, DC capacitor voltage and slope of the reference compensator current wave. Simulation results, obtaining using Matlab/Simulink, show the effectiveness of fuzzy logic controllers in optimizing the PWM technique of the active filter with constant switching frequency**.

Index Terms— **active power filter, fuzzy logic theory, constant switching frequency, harmonic compensation.**

I. INTRODUCTION

Harmonic voltage level in electrical supply systems have been growing continuously throughout the last years. This growth caused by rising use of power electronics as in variable speed drives or power supply units for home, office IT devices. The harmonics cause problems in power systems and in consumer products such as equipment overheating, capacitor blowing, motor vibration, excessive neutral currents and low power factor. Harmonic current pollution also has serious consequences such as increased power system losses, quick aging of materials, excessive heating in rotating machinery, and significant interference with communication circuits. The shunt active power filters (APF), generally based on a voltage source inverter structure, and seems to be an attractive solution to harmonic current pollution problems. It can be used to compensate unbalanced currents, current harmonics, and reactive power. The main currents, obtained after compensation, are then sinusoidal and in phase with the supply voltages [1], [2]. Fig. 1 shows the schematic diagram of a three-phase four-wire shunts APF, where the APF senses the source voltages and load currents to determine the desired compensation currents [3].

Up to date, most reference compensation current strategies of the APF are determined either with or without reference-frame transformations. Among many approaches for determining the APF reference compensation currents, one of the mainstreams is to maintain sinusoidal source currents supplying average real power to the load.

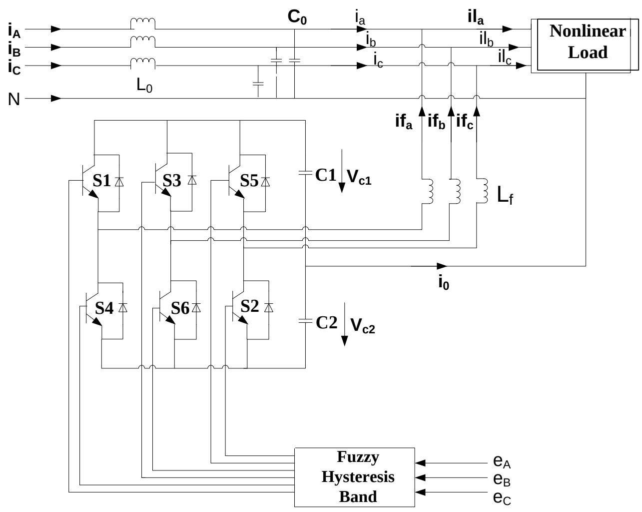

Fig. 1. Main circuit topology of power filter

With the use of sinusoidal source current strategy, it is proved that the APF can have better performance than other strategies [4]. To achieve full compensation of both reactive power and harmonic/neutral currents of the load, applied a method to determine the shunt APF reference compensation currents, even if the source voltages and load currents are both imbalanced and distorted.

The studied method is similar to those presented in [5]–[6], it is an a-b-c reference-frame-based method and is categorized as a sinusoidal source current strategy [7].

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In other main part of studied APF, PWM technique is optimized with fuzzy logic theory application. Among the various PWM techniques, the hysteresis band current control PWM is popularly used because of its simplicity of implementation. This technique does not need any information about the system parameters, but has the disadvantage of uncontrolled frequency. As a result, the switching losses are increased and current sources contain excess ripples [8].

In drive applications, hysteresis current control is probably the simplest technique used to control the phase motor currents for ac machine speed drive systems, because of its ease of implementation, fast current control response, and inherent peak current limiting capability. However, depending on load conditions, switching frequency may vary widely during the fundamental period, resulting in irregular inverter operation.

This is mainly due to the interference between the commutation of the three phases, since each phase current not only depends on the corresponding phase voltage but also is affected by the voltage of the other two phases. Thus the actual current waveform is not determined by the hysteresis control, the current slope may vary widely and current peaks may appreciably exceed the limits of hysteresis bands [9].

To overcome these problems the current controller performance can be improved by using the adaptive control system theory. A new technique, based on the same concept, but with the hysteresis band implemented with fuzzy logic, is proposed to optimize the PWM performance. This approach permits us to define a systematic computing of a look-up control using the instantaneous supply voltage and mains current reference slope as input variables and the hysteresis band as an output variable to maintain the modulation frequency constant.

For the DC supply source of the three phase active filter, PI controller is applied. Simulation results are presented to verify the proposed method and control strategy.

II. DETERMINING APF REFERENCE CURRENT COMPENSATION

Compensation strategy of the active power filter is based on the requirement that the source currents need to be balanced, undistorted, and in phase with the positive-sequence source voltages. The goals of the shunt APF control are 1) unity source power factor at positive-sequence fundamental frequency 2) minimum average real power consumed or supplied by the APF 3) harmonic current compensation and 4) neutral current compensation. Therefore, the active power filter must provide full compensation (i.e., harmonic/neutral currents and reactive power) for the nonlinear load. To achieve these goals, the desired three-phase source currents must be in phase with the positive-sequence fundamental source voltage components.

The reference compensation current calculator is given in (1). Fig. 2 depicts the block diagram of the control circuit based on the used approach to fulfill the function of the reference compensation current calculator. In Fig. 2, the three-phase fundamental voltage components are extracted by using a low-pass filter.

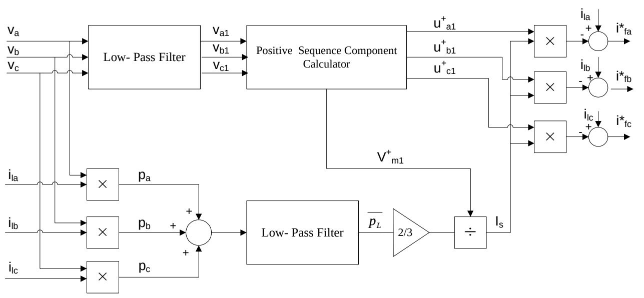


Fig. 2. Block diagram of the control circuit for calculating APF reference current

Under the constraints that the load average real power is supplied by the source and the APF does not provide or consume any average real power, it is required to find the current amplitude is from the sequential instantaneous voltage and real power components.

The required current injection at each phase by the shunt APF is then obtained by subtracting the desired source current from the load current as given in (1) [7].

$$i_{fk}^{*} = i_{lk} - \frac{2\overline{p}_l}{3\left(V_{m1}^{+}\right)^2} v_{k1}^{+} \qquad (1)$$

III. HYSTERESIS BAND CURRENT CONTROLLER

A. Basic Function Principle

The power circuit of the shunt active filter under investigation [10] consists of two anti-parallel 6pulse bridges with two capacitors in series on the dc-side. One bridge is built of solid state switching devices allowing pulse modulation, the other of diodes. As the connecting point between the capacitors *C+* and *C-* is connected to neutral, compensating currents can be injected independently in each phase. Fig. 3 shows a bridge section of the compensator with the source voltage u_N at its coupling point and *uc+* and *uc-* as capacitor voltages.

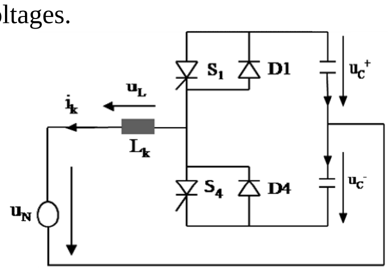


Fig. 3. Single phase bridge of the shunt active filter

Table I shows the switching states of the switching devices S1, S4 and diodes D1, D4, the voltage u_L over the coupling inductance L_k and capacitor currents ic+ and ic-. Depending upon the polarity of the compensating current i_k and the deviation $\Delta i_k = i_{kref} - i_k$ of its reference value $i_{kref.}$ The reference value is provided by the filter's control circuit.

TABLE I
POSSIBLE SWITCHING STATES OF THE SOLID- STATE DEVICES AND CORRESPONDING VOLTAGES AND CURRENTS

i_k	Δi_k	S_1	S_4	D_1	D_4	u_l	i_c^+	i_c^-
>0	<0	0	0	0	1	$-u_c^- - u_N$	0	i_k
>0	>0	1	0	0	0	$u_c^+ - u_N$	$-i_k$	0
<0	<0	0	1	0	0	$-u_c^- - u_N$	0	i_k

<0	>0	0	0	1	0	$u_c^+ - u_N$	$-i_k$	0

Permissible switching times are determined by using a fixed time pattern depending on the maximum switching frequency of the solid-state devices. Hysteresis control is used to derive the gating signals, so Fig. 5 shows the two state of hysteresis control.

B. Hysteresis Band Width Calculation (Analytical Method

The width of the hysteresis band determines the switching frequency of the inverter. As the bandwidth narrows the switching frequency increases. A suitable bandwidth should be selected in accordance with the switching capability of the inverter. The bandwidth should also be selected small enough to supply the reference current precisely. The bandwidth of the hysteresis current controller determines the allowable current shaping error. By changing the bandwidth the user can control the average switching frequency of the active power filter and evaluate the performance for different values of hysteresis bandwidth. In principle, increasing the inverter operating frequency leads to get a better compensating current waveform. However, because of the switching device limitations, increasing the switching frequency causes more switching losses than before.

The hysteresis-band current control method is popularly used because of its simplicity of implementation among the various PWM techniques. Besides fast-response current loop and inherent-peak current limiting capability, the technique does not need any information about system parameters. However, the current control with a fixed hysteresis band has the disadvantage that the switching frequency varies within a band because peak to peak current ripple is required to be controlled at all points of the fundamental frequency wave.

According to [11] and [12], fig. 5 shows the PWM current and voltage waves for phase-a. When the actual line current of the active power filter tries to leave the hysteresis band, the suitable power transistor is switched to ON or OFF state to force the current to return to a value within the hysteresis band. Then the switching pattern will be trying to maintain the current inside the hysteresis band. The currents i_{fa} tends to cross the lower hysteresis band at point 1, where upper side IGBT of leg *"a"* is switched on. The linearly rising current then touches the upper hand at point 2, where the lower side IGBT of leg *"a"* is switched on.

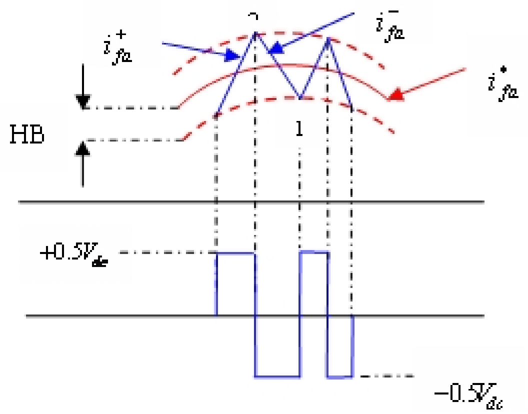


Fig.5. Voltage and current waves with hysteresis band current control.

The following equations can be written in the respective switching intervals t_1 and t_2 from Fig. 5, can be written

$$\frac{di^+_{fa}}{dt} = \frac{1}{l}\left(0.5V_{dc} - V_s\right) \qquad (2)$$

$$\frac{di^-_{fa}}{dt} = -\frac{1}{l}\left(0.5V_{dc} + V_s\right) \qquad (3)$$

From the geometry of Fig. 5 can be written:

$$\frac{di^+_{fa}}{dt}t_1 - \frac{di^*_{fa}}{dt}t_1 = 2HB \qquad (4)$$

$$\frac{di^-_{fa}}{dt}t_2 - \frac{di^*_{fa}}{dt}t_2 = -2HB \qquad (5)$$

$$t_1 + t_2 = T_c = \frac{1}{f_C} \qquad (6)$$

Where t_1 and t_2 are the respective switching intervals, and f_c is the switching frequency. Adding (4) and (5) and substituting (6), it can be written:

$$t_1\frac{di^+_{fa}}{dt} + t_2\frac{di^-_{fa}}{dt} - \frac{1}{f}\frac{di^*_{fa}}{dt} = 0 \qquad (7)$$

Subtracting (5) from (4), so:

$$t_1 - t_2 = \left(\frac{di^*_{fa}}{dt}\right) \Big/ f_c\left(\frac{di^+_{fa}}{dt}\right) \qquad (8)$$

Finally:

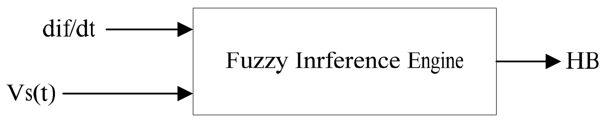
$$HB = \left\{\frac{0.125Vdc}{Lf_c}\left[1 - \frac{4L^2}{V_{dc}^2}\left(\frac{v_s}{L} + m\right)^2\right]\right\} \qquad (9)$$

f_c is the modulation frequency and $m = di^*_{fa}/dt$ is the slope of command current wave. Hysteresis band (HB) can be modulated at different points of fundamental frequency cycle to control the switching pattern of the inverter.

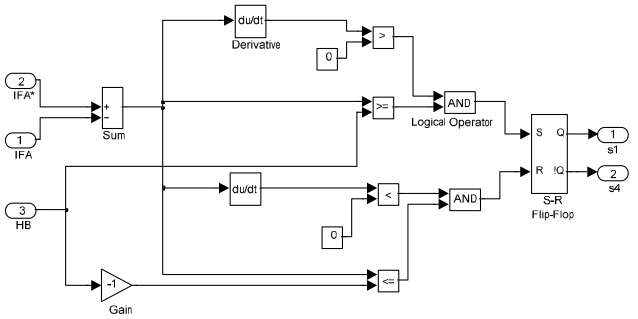
According to HB formula in equation (9), calculation of HB under constant f_c depends on system parameters as L, V_{dc}, …so solving this problem in drive applications and loads type as motor are very complex.

IV. PROPOSED FUZZY HYSTERESIS BAND CURRENT CONTROL

Fig. 6 shows a block diagram of the adaptive hysteresis band current control.



a) Fuzzy hysteresis current band scheme



b) Logical circuit for S1&S4 firing

Fig.6. Simplified model of an adaptive or fuzzy hysteresis band current control.

To improve the active filter performance without precise knowledge of the APF parameters, the hysteresis band value can be implemented with a fuzzy logic controller.

In this case, the supply voltage wave, v_s (t) and filter current reference slope, di_f^*/dt can be selected as input variables to the fuzzy controller, and the hysteresis band magnitude (HB) as an output variable.

A. Fuzzification

Fig. 7 and Fig. 8 show the principal fuzzy variable quantization scheme used here. It is composed of five triangular-shaped membership functions with the respective linguistic labels shown. In terms of the so-called universe of discourse, i.e., [-1, 1] and [0, 1], each membership function is defined by the set of three numbers {b1, c1, b2}, which represent, respectively, the values of the universe of discourse corresponding to the left minimum, peak, and right minimum of the triangle representing the particular membership function. Thus, the five membership functions shown in Fig. 7 are defined as negative large (NL), negative medium (NM), zero (ZE), positive medium (PM) and positive large (PL) and the corresponding membership functions for HB shown in Fig. 8 are defined as positive very small (PVS), positive small (PS), positive medium (PM), positive large

(PL) and positive very large (PVL). The fuzzification function given by

$$F(x_0): [-1, 1] \text{ to } [0, 1]$$

is applied to variable Vs(t) and dif*/dt in order to determine their fuzzy numbers between zero and one when the input measurement are Vs_0(t) and dif_0*/dt, respectively.

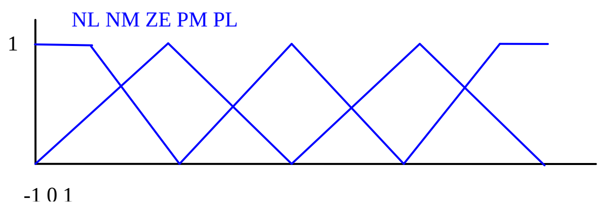


Fig.7. Membership functions for the input variables dif*/dt and vs(t)

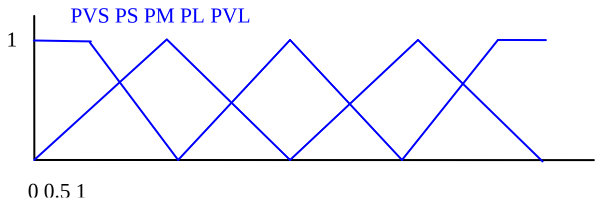


Fig.8. Membership function for the output variable HB

B. Fuzzy Rule Base

In our application, which is actually tracking problem, the fuzzy controller output, which is the width of hysteresis band, is made to control the switching frequency nearly constant. In FHBC (Fuzzy Hysteresis Band Controller) Vs(t) and dif*/dt are the inputs and HB is the output. Therefore, a rule base is needed that relates pairs of Vs (t) and dif*/dt to values of HB. Since there are five membership functions each for Vs (t) and dif*/dt, as defined in Fig. 7, there are 25 possible combinations of Vs (t) and dif*/dt. For each of these, there is a corresponding membership function, whose linguistic label can be determined using standard IF-THEN fuzzy rules in the form.

IF Vs (t) is **NL** and dif*/dt is **NL** THEN HB is **PVS**

Where NL, NL, and PVS are fuzzy subsets that represent the linguistic labels of Vs (t) and dif*/dt and HB, respectively.

There are 25 such statements, which are stated concisely in the matrix shown in Table II. This matrix is known as the fuzzy rule base. The determination of these rules for FHBC is based on equation (9). To illustrate the use of Table II, suppose that according equation (9) Vs (t) is PL and dif*/dt would be ZE, and it would be necessary for the HB to make a positive large change in order to force switching frequency constant. Thus, HB is large and positive (PL), as shown in Table II.

TABLE II RESULTING INFERENCE RULES

v_s / di_f/dt	NL	NM	ZE	PM	PL
NL	PVS	PS	PS	PM	PM
NM	PS	PS	PS	PM	PM
ZE	PL	PL	PVL	PL	PL
PM	PM	PM	PS	PS	PS
PL	PM	PM	PS	PS	PVS

C. Inference Engine and Defuzzification

In order to determine a specific or crisp value for HB, the rule base has to be used to with an inference method or engine, followed by defuzzification. Here, the popular mamdani' minimum fuzzy implication and max-min compositional rule are used for inference.

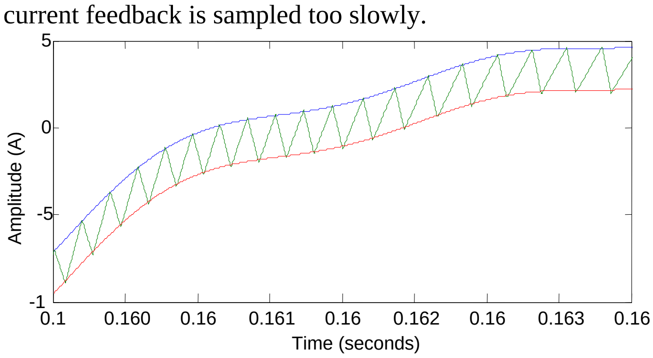
V. SIMULATION RESULTS

A. Sampling frequency

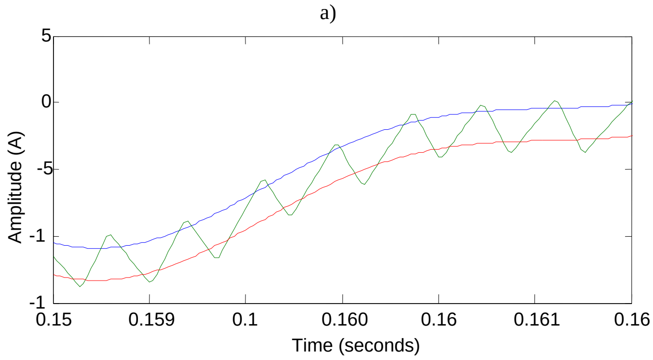
Hysteresis current control requires current feedback. The sensed current is compared to the hysteresis limits and the result of this comparison is used to control the switches in the inverter. In an analogue system the comparisons are made continuously and the current will be forced to stay within the hysteresis band at all times. With a digital controller, events happen at discrete intervals. The sensed current is digitized and the comparisons are made digitally.

The current information is updated at the sampling frequency of the analogue to digital converter (ADC) that samples the current feedback. If this sampling frequency is too low there is a chance that the current will have exceeded the hysteresis limits by the time the comparison is made.

Fig. 9 shows the results of a simulated inverter controller with two different sampling frequencies. It can be seen that the current regularly exceeds the hysteresis band when the current feedback is sampled too slowly.



2×10-6 second sampling time
a)



20×10-6 second sampling time
b)

Fig. 9 A higher sampling frequency reduces the level of current overshoot from the hysteresis limits.

A smaller inductor in APF will give a higher *di/dt* and so the current overshoot will be greater. The worst case is where the current is just inside the hysteresis band when the comparison is made. The current will then continue on past the limit and will only reverse direction at the next sampling point.

To illustrate the APF employing conventional fix hysteresis band and fuzzy hysteresis band, the following specifications for load are considered as Table III and waveform of load current is shown in Fig. 10.

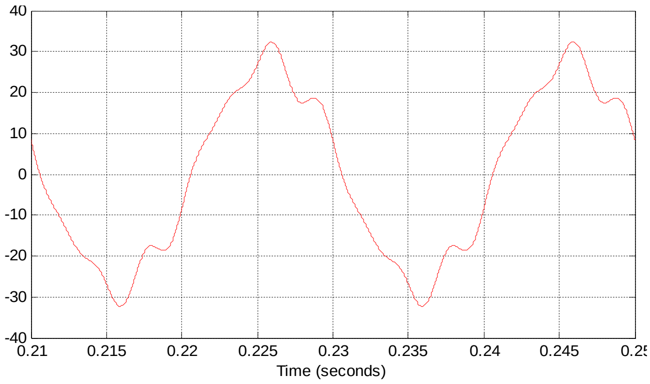


Fig. 10 Load current in phase-a

TABLE III SPECIFICATIONS OF LOAD TYPE-I

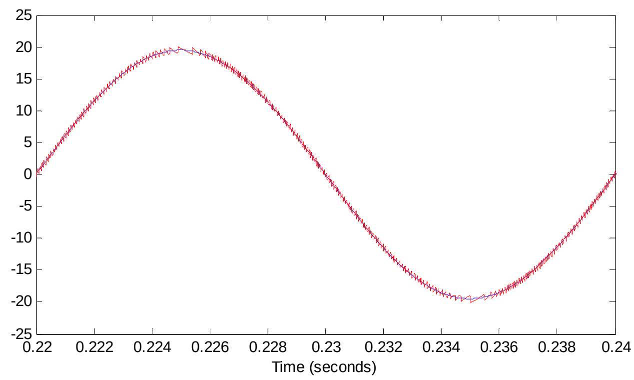
HARMONIC ORDER			*1*	*3*	*5*	*7*
Source Voltage	A	AMPLITUDE	220	0	0	0
		PHASE	0	0	0	0
	B	AMPLITUDE	220	0	0	0
		PHASE	-120	0	0	0
	C	AMPLITUDE	220	0	0	0
		PHASE	120	0	0	0
Non- Linear Load	A	AMPLITUDE	14	0	3	2
		PHASE	-15	0	-60	30
	B	AMPLITUDE	11	0	3	2
		PHASE	-87	0	60	-80
	C	AMPLITUDE	11	0	3	2
		PHASE	-15	0	-70	125
Linear Load		L(mH)			R(ohm)	
	A	12			15	
	B	11			16	
	C	20			18	

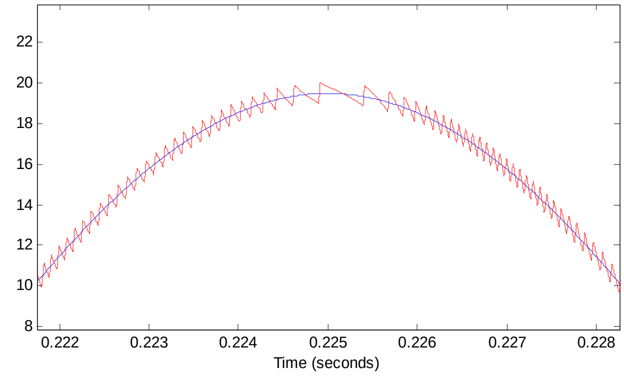
In the form of analytical method load currents in three phases are followed as:

$$i_{La}(t) = 14\sin(wt - 15^0) + 3\sin(5wt - 60^0) + 2\sin(7wt + 30^0)$$

$$i_{Lb}(t) = 11\sin(wt - 87^0) + 3\sin(5wt + 60^0) + 2\sin(7wt - 80^0)$$

$$i_{Lc}(t) = 11\sin(wt - 15^0) + 3\sin(5wt - 70^0) + 2\sin(7wt + 125^0)$$





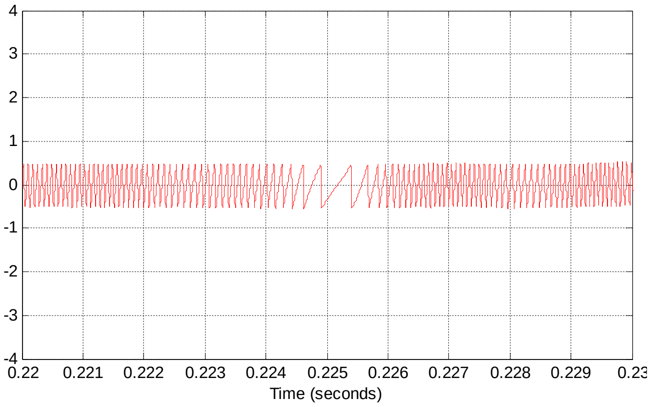


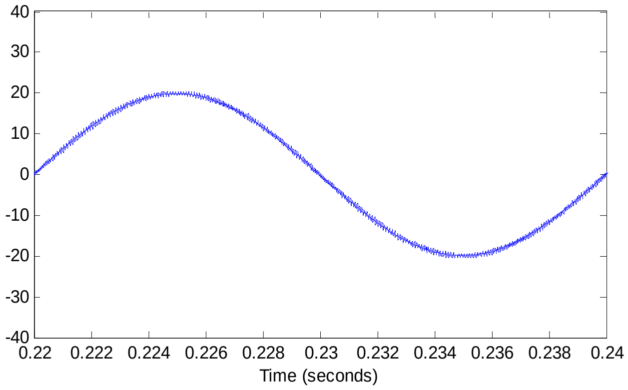
Fig.11. Supply current, tracking shunt active filter for phase-a and current error for conventional fix hysteresis band

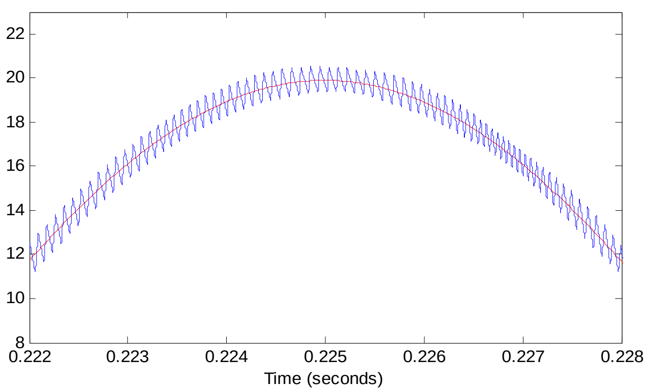
Fig. 11 shows the supply current, tracking shunt active filter for phase-a and current error waveforms for fixed hysteresis current control, where the fixed band was set to achieve a maximum switching frequency of 12.5 kHz.

Due to the interaction of three-phase current controller, the supply current instantaneous error can go beyond hysteresis band 'h' and reach up to '2h'. The supply current and current error waveforms for fuzzy hysteresis band current control shown in Fig. 12.

The supply current FFT for fixed hysteresis current control and fuzzy hysteresis band current control are shown in Fig. 13 and Fig. 14 respectively. In fixed hysteresis current control, the supply current harmonics are widely distributed from hundreds of Hertzs to several kiloHerts frequency.

However, for fuzzy hysteresis band current control, a switching frequency is held in 12.5 kHZ, and thus the supply current harmonics are concentrated around 12.5kHz frequency. This provides predictability of the converter input current harmonics, avoids resonance problem and makes the filter design task easier.





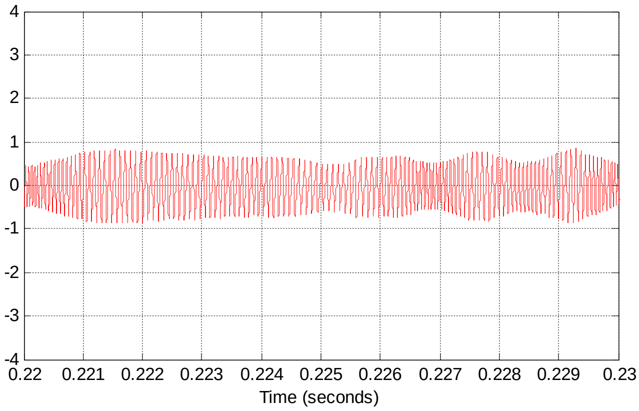


Fig.12. Supply current, tracking shunt active filter for phase-a and current error for fuzzy hysteresis band

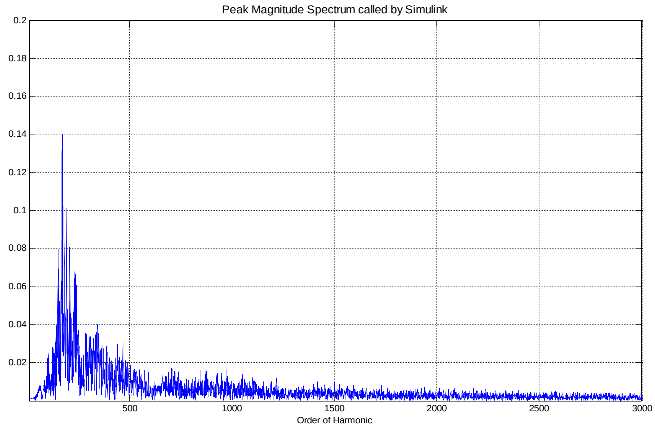


Fig.13. Supply current FFT for fuzzy hysteresis band current control

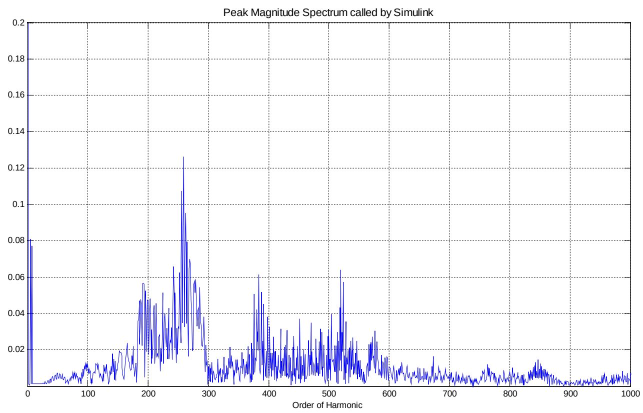


Fig.14. Supply current FFT for conventional fixed hysteresis band current control

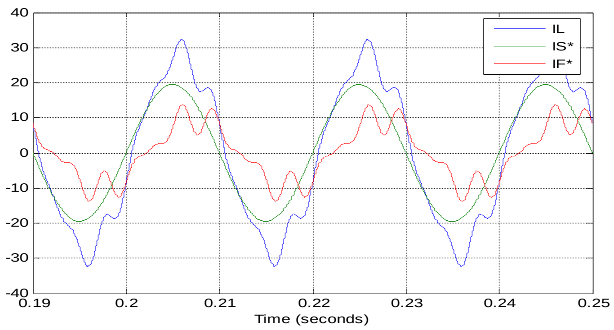


Fig.15. Load Current, Source Current and APF Current in phase a in conventional fix hysteresis band and fuzzy hysteresis band

Fig. 15 shows the load current, APF injection current, and the source current after compensation at phase a, respectively.

Fig. 16 depicts the source current and positive-sequence fundamental source voltage at phase-a after APF compensation.

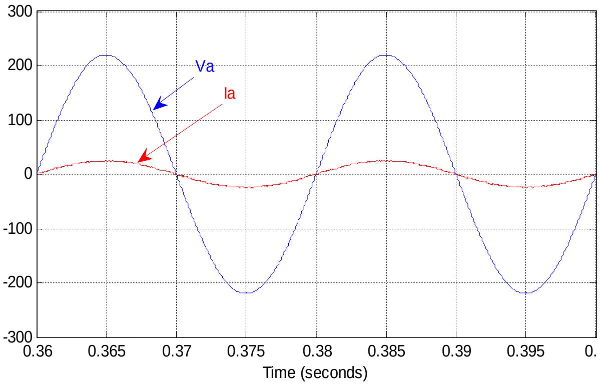


Fig.16 Near unity power factor in phase-a for conventional fix hysteresis band and fuzzy hysteresis band

For estimate inverter losses, the data of the switching devices, i.e., IGBT and anti-parallel diode given in Table IV are considered. Inverter losses are also divided into two categories, i.e conduction loss and switching loss in both the devices.

TABLE IV
SEMICONDUCTOR DEVICE SPECIFICATION

Parameters	*Numerical Value*
Turn – on time Turn – off time	0.55μs 1.8 μs
Collector – emitter Saturation VOLTAGE	3.0 V
Diode forward voltage Reverse recovery current Reverse recovery time	2.5 V 230 A 0.15 μs

Where, $t_{sw(on)}$ and $t_{sw(off)}$ are the IGBT turn-on and turn-off times respectively, $I_{sw(pk)}$ is the peak current switched by IGBT, I_{rr} and t_{rr} are diode peak reverse recovery current and reverse recovery time respectively, $V_{CE(pk)}$ is the peak voltage across diode at recovery. Figs. 17 and 18 show that the inverter switching loss of APF using fuzzy hysteresis band current controller is compared with that of the APF using conventional fixed hysteresis band.

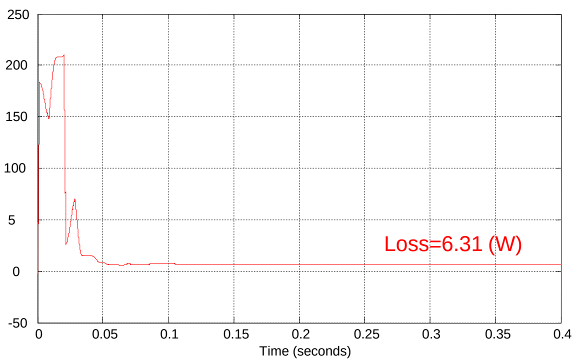


Fig.17. Switching losses in APF with fuzzy hysteresis band current controller

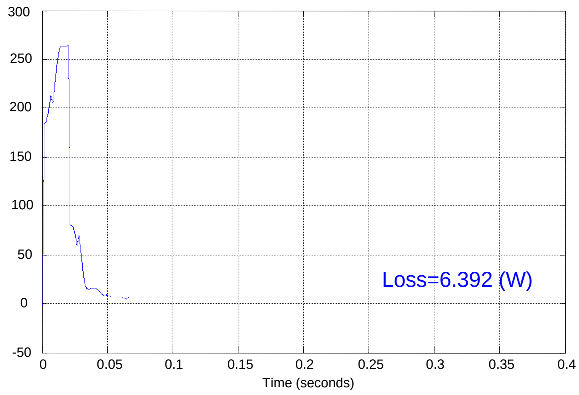


Fig.18. Switching losses in APF with fixed hysteresis band current controller

Conduction loss is calculated using the actual currents through the IGBT and anti-parallel diodes during the conduction period of the devices. Calculation of conduction loss requires values of IGBT collector-emitter saturation voltage drop V_{CE} (sat) and diode forward voltage drop V_{EC}, both given in Table IV. According to [14], switching loss comprises of IGBT turn-on pulse turn-off losses (Psw) and diode reverse recovery loss (Prr) obtained using following expressions:

$$Psw = f_c V_{dc} I_{sw(pk)} (t_{sw(on)} + t_{sw(off)})/2\pi$$

$$Prr = 0.125 I_{rr} t_{rr} V_{CE\ (pk)} f_c$$

In conventional fix band hysteresis current control and fuzzy hysteresis band current control method, instantaneous switching frequency with waveform of upper band, lower band and variation of inductor current in domain of upper and lower band are shown in Fig. 19, 20 respectively.

The variable fuzzy hysteresis current band with instantaneous waveforms of dif/dt and Vs(t) are shown in Fig. 21.

The % total harmonic distortion (%THD) of the supply current using conventional fix hysteresis band current controller and fuzzy hysteresis band current controller are shown in Table VI.

TABLE VI
TOTAL HARMONIC DISTORTION

	THD (%)	
	Fixed H.B	Fuzzy H.B
Load Type-I	3.8	2.6

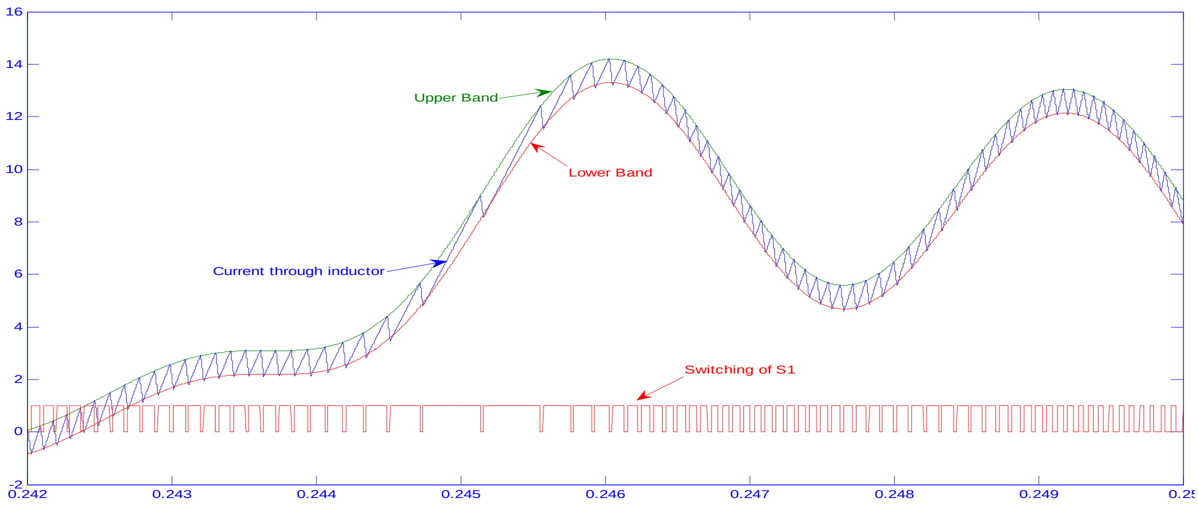


Fig. 19 Variation of inductor current in fixed hysteresis band and switching of S1

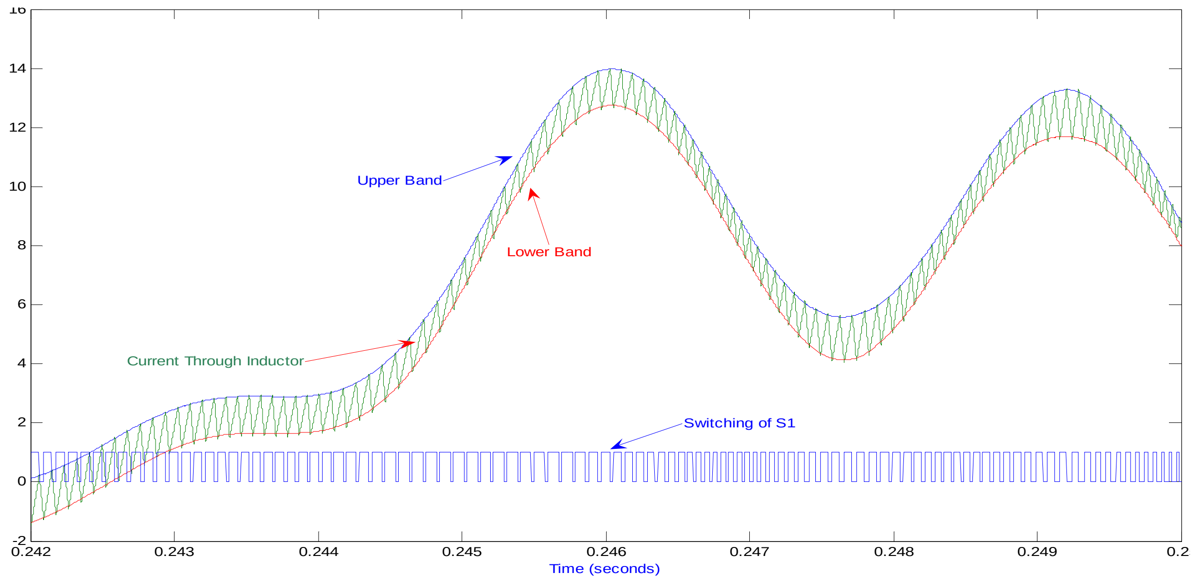


Fig. 20. Variation of inductor current in fuzzy hysteresis band and switching of S1

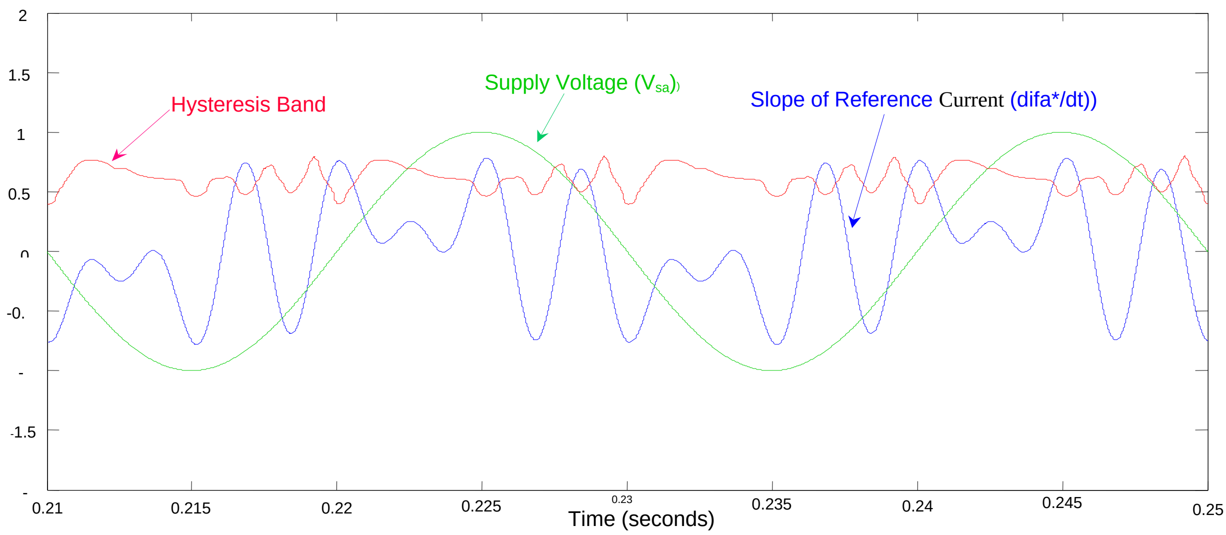


Fig. 21. Variation of hysteresis band (fuzzy H.B) adeptly as inputs slop of reference current and source voltage

VI. CONCLUSIONS

The simulations are done with both the fuzzy hysteresis band and the conventional fixed band current control method. At the fuzzy method, the switching frequency of PWM inverter is nearly held constant, so switching loss is lower than fixed hysteresis band method.

The harmonic components of a phase current are concentrated around the near switching frequency. And thus it can be verified that fuzzy hysteresis band method has a high performance for current control.

According to Table VI, amount of THD in fuzzy hysteresis band method is lower than fixed hysteresis band.

The conventional fixed hysteresis band current control achieves fast response but generates excessive current ripples because the modulation frequency varies within one band. With the fuzzy hysteresis current control method, the band can be easily implemented with fuzzy logic to keep the modulation frequency nearly constant and to achieve good quality filtering.

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