Fixed and Sinusoidal-Band Hysteresis Current Controller for PWM Voltage Source Inverter with LC Filter

Mohamayee Mohapatra, B.Chitti Babu, *Member IEEE*
Department of Electrical Engineering, National Institute of Technology, Rourkela, INDIA
E-mail: mohamayee@gmail.com, bcbabunitrkl@ieee.org

Abstract- **For improving the dynamic response of the system, most of the pwm voltage source inverters are operating with inner current control loop. The application includes high performance ac drives, active filters and power supplies etc. Recently pwm voltage source inverters are employed in grid connected distributed power generating systems in order to provide secure and reliable power to the utility grid. This paper presents the comparative study between fixed and sinusoidal hysteresis current controller for pwm voltage source inverter. A comparison has been made in terms of THD level at the three-phase load current, current error minimization, average and maximum switching frequency of the converter switches in VSI. The simulation study has been carried out with the help of MATLAB simulink environment and the performance of such controllers has been observed during load variations.**

Index terms – **Voltage source Inverter (VSI), Current Control, Total Harmonic Distortion (THD), switching frequency, current error.**

I. Introduction

Pulse width modulation (PWM) techniques have been the subject of intensive research during the last few decades. PWM technique using sine wave triangular carrier wave intersection was first proposed by Schonung and Stemmler in 1964. PWM current-controlled voltage source inverters are widely used in high performance ac drives for quick response and accurate control. It has substantial advantage in eliminating stator dynamics in high performance ac drive systems under field orientation control.

A variety of current controlled techniques have been studied and reported in the literature. They are classified as linear and non-linear current controllers. Linear controller includes PI controller, state feed back controller and predictive current controller. Nonlinear controller includes bang-bang controllers (Hysteresis control, ramp type control and delta modulator) and predictive controllers with online-optimization [1]. Recently fuzzy logic and neural network based current controllers are also discussed as well. Linear current controller requires the complete knowledge of load parameters and it needs more calculation, where as non-linear current controller does not need the load information and it provides good dynamic response to the system. Brod & Novotny [2] had given an overview of several current controllers e.g. hysteresis and ramp comparison controller in greater depth. This controller produces a synchronous, sine triangular PWM with current error acting as the modulating wave. It has the advantage of limiting the maximum inverter switching frequency to the triangular wave form frequency and producing well defined harmonics .But it has disadvantage that multiple crossing of the ramp may become a problem, when the time rate of change of the current error exceeds that of the ramp. Thus inherent phase and amplitude errors arise during steady state condition. An improved ramp comparison technique is proposed to overcome some of the drawbacks of conventional current controllers. Two hysteresis current control methods (hexagon and square hysteresis band controls) of three-phase VSI is presented in [3-5].

Among the various PWM techniques, the hysteresis band current control is used very often because of its simplicity. Besides fast response current loop, the method doesn't need any knowledge of load parameters. But it has the disadvantage that the switching frequency is irregular and current ripple is relatively large. B.K.Bose[6] proposed an adaptive hysteresis band current control PWM technique. The hysteresis band can be programmed as a function of load and supply parameters in order to maintain a fixed modulation frequency. Both fixed & sinusoidal band hysteresis current controller is studied with and without lockout circuit compared in [7].

This paper describes a fixed and sinusoidal band hysteresis current controller with a low pass filter (LC filter).In fixed band, the hysteresis band is fixed whereas in sinusoidal band the hysteresis bands vary over a fundamental period. The fixed-band hysteresis controller gives good performance except that the switching frequency is irregular and current ripple is relatively large. But in a sinusoidal band hysteresis current controller, the ripple can be varied with the current magnitude thereby reducing the current ripple content. A low pass filter is used to minimize the ripple and hence minimize the higher order harmonic content. So a lesser ripple would result in a lower harmonic content keeping infact the fast response and simplicity of implementation of hysteresis current controllers. A comparison has been made in terms of THD level at the three-phase load current, current error minimization, average and maximum switching frequency of the converter switches in VSI. The simulation study has been carried out with the help of MATLAB Simulink environment and the performance of such controllers has been observed during load variations.

II. Basic Structure of VSI with Hysteresis Current Controller

The basic structure of pwm voltage voltage source inverter with hysteresis controller is shown in the fig.1. In this circuit three phase RL load is connected to the pwm voltage source inverter. The load currents i_a, i_b and i_c are compared with the reference currents i_a*, i_b* and i_c* and error signals are passed through hysteresis band to generate the firing pulses, which are operated to produce output voltage in manner to reduce the current error. The principle of Hysteresis current control is very simple. The purpose of the current controller is to control the load current by forcing it to follow a reference one. It is achieved by the switching action of the inverter to keep the current within the Hysteresis band. The load currents are sensed & compared with respective command currents by three independent Hysteresis comparators having a hysteresis band 'h'.The output signal of the comparators are used to activate the inverter power switches. The inverter switches produces six active vectors and two inactive vectors according to the switching sequence and the hysteresis controllers impose dead band in the α-β plane which forms hexogen which is shown in the fig.2. The concept of voltage (current) vector is defined as [1], because it is a very convenient representation of a set of three phase voltages.

The voltage vector is defined as

$$v = \tfrac{2}{3}\left[v_a + a v_b + a^2 v_c\right) \quad (1)$$

where $a = e^{\frac{j2\pi}{3}}$, v_a, v_b, v_c are phase voltages. Similarly, the inverter current vector is defined as

$$i = \tfrac{2}{3}\left[i_a + a i_b + a^2 i_c\right] \quad (2)$$

The actual voltage can be recovered from v

$$\begin{aligned} v_a &= [v]\cos\theta \\ v_b &= [v]\cos\left(\theta - \tfrac{2\Pi}{3}\right) \\ v_c &= [v]\cos\left(\theta + \tfrac{2\Pi}{3}\right) \end{aligned} \quad (3)$$

Where θ is the angle between voltage vector and real axes

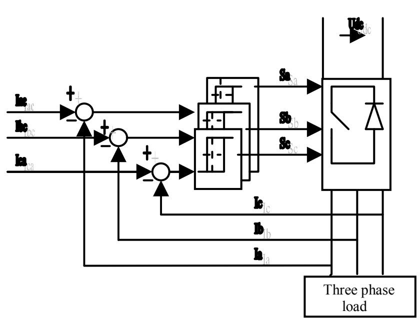


Fig.1.Three-phase VSI with Hysteresis current controller

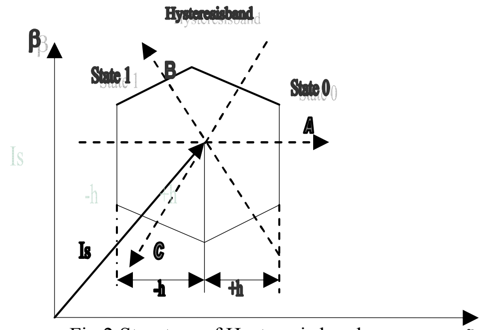


Fig.2.Structure of Hysteresis band

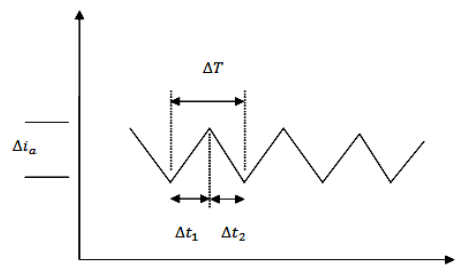


Fig.3.Switching current waveforms

III. Analysis of Hysteresis Current Controller

A. *Maximum and Average Switching Frequency*

From the reference [8], the maximum inverter switching frequency is defined as

$$MSF = \frac{1}{T_1 + T_2} \quad (4)$$

where T_1 and T_2 are minimum ON and OFF periods available to a device to switch from previous OFF and ON states, respectively. For high power-factor load, where the power factor is always more than 80%, the MSF occurs near the zero crossing points of the reference current waveform. Considering the worst case Condition (Fig. 4), when one of the upper switches of an inverter is turned ON, the load current will reach P from A in time *T1=AB,* The slope of the reference current at $t=T/2$ *is* $di/dt_{t=T/2} = 2\pi f_m M$. Assuming the line *PD* to be in parallel to the tangent drawn on the reference current at *T/2* and *PQ* a line parallel to *AB,* from the geometry of Fig.4. *AD=AQ +QD=2 β*, with the identities *[AQ=PB=AB tan* α=T_1 *tan* α and *QD=PQ tan (DPQ) =T1* $(2\pi f_m M)$*], T1* is approximately given by

$$T_1 = \frac{2h}{2\pi f_m M + m} \text{ sec} \quad (5)$$

where

M= peak value of reference sine wave;

f_m= frequency of the reference current waveform;

m=slope of the reference current *(di/dt)*

+/- *h* hysteresis band.

If we assume T2=T1, then MSF becomes

$$MSF = 1/(T1+T2) \approx \frac{2\pi f_m M + m}{4h} \text{ Hz} \quad (6)$$

Considering a sampling (simulation) rate of $\boldsymbol{N}$ per cycles, current increment of S in the sampling (simulation) interval, the current slope m can be written as

$$m = \frac{S}{1/f_m N} = S f_m N \text{ A/sec} \tag{7}$$

As a result, the MSF becomes

$$MSF_{fixed} = \frac{f_m (SN + 2\pi M)}{4h} \text{ Hz} \tag{8}$$

For the sinusoidal hysteresis band, in the worst case condition both T_1 and T_2 can be as low as one sampling interval [8].Thus

$$(MSF)_{\sin} = \frac{f_m N}{2} \tag{9}$$

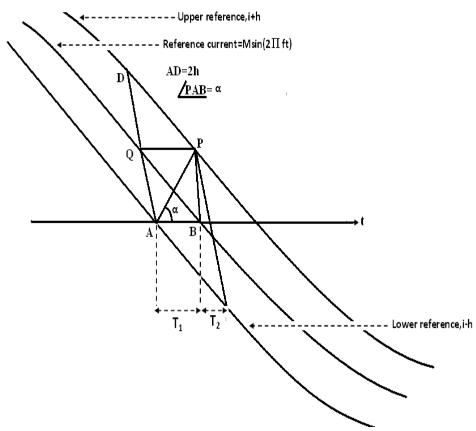


Fig.4. Determination of MSF of the fixed-band current controller.

The average switching frequency (ASF) is defined as

$$ASF = {}^{N_S}\!/_{T} \text{ Hz} \tag{10}$$

Where

N_s=Number of switching in one fundamental period

T=fundamental period

B. *Fixed Band Scheme*

In this scheme, the hysteresis bands are fixed throughout the fundamental period. The algorithm for this scheme is given as

$I_{ref} = I_{max} \sin\omega t$ (11)

Upper band $i_{up} = i_{ref} + h$

Lower band $i_{low} = i_{ref} - h$ (12)

Where h = Hysteresis band limit

If $i_a > i_{up}$, $V_{ao} = -V_{dc}/2$

If $i_a < i_{lo}$, $V_{ao} = + V_{dc}/2$.

C. *Sinusoidal Band Scheme*

In this scheme, the hysteresis bands vary sinusoidally over a fundamental period. The upper and lower bands are given as

$I_{ref}=I_{max}\sin\omega t$

Upperband $i_u = (I_{max}+h) \sin(\omega t)$ (13)

Lowerband $i_{lo}=(I_{max}-h)\sin(\omega t)$

The algorithm is given as follows:

For $i_{ref}>0$:

If $i_a>i_u$, $V_{ao} = -V_{dc}/2$ (14)

If $i_a<i_u$, $V_{ao} = +V_{dc}/2$

For $i_{ref}<0$:

If $i_a<i_u$, $V_{ao} = +V_{dc}/2$ (15)

If $i_a<i_u$, $V_{ao} = -V_{dc}/2$

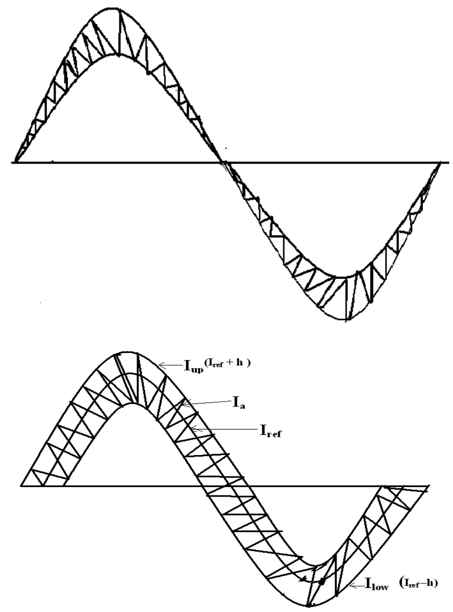


Fig.5.Band shape of the Hysteresis Controller a) Fixed-band controller b) Sinusoidal-band controller

IV. FILTER DESIGN ON LOAD SIDE

The fixed band current controller gives good dynamic performance; but switching frequency is irregular and current ripple is large. In the case of sinusoidal band current controller the ripple can be varied with the current magnitude thereby reducing the current ripple content. In sinusoidal band as compared to fixed band current ripple content is less, but still the load current contains higher order harmonics that cause EMI problems and device heating. These high order harmonics are easily filtered out by using low pass filter on the load side. The Low pass filter (LC) with proposed configuration is shown in the Fig.(6)

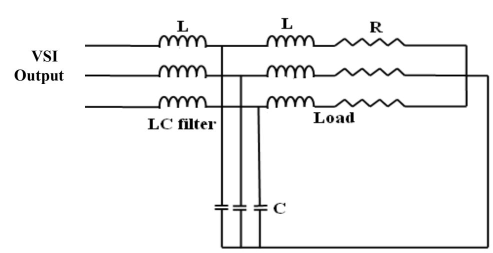


Fig.6. Low-pass filter with LC components

For designing the LC filter to eliminate the higher order harmonics, following calculations are made.

a) I_{ref}=10A;
b) Load parameters R= 3Ω, L=5mH;
c) Frequency=50 Hz.

The inductive reactance for the n[th] harmonic voltage is

$$X_L = j2n\Pi \times 50 \times 5 \times 10^{-3} = j1.570796327\,n\Omega \qquad (16)$$

The impedance for the n[th] harmonic voltage is

$$|Z_n| = \left[3^2 + (1.57079632n)^2\right]^{1/2} \qquad (17)$$

Where n=order of harmonics

The n[th] and higher order harmonics would be reduced significantly if the filter impedance is much smaller than that of load, and a ratio of 1:10 is normally adequate,

$$|Z_n| = 10X_e$$

Where the filter impedance is

$$|X_e| = \left[(X_l)^2 - (X_c)^2\right]^{/2}$$

$$|X_e| = \left[(2\times n\times\Pi\times 50\times L)^2 - (1/(2\times n\times\Pi\times 50\times C))^2\right]^{1/2} \qquad (18)$$

Putting L=0, equation (18) becomes

$$\left[3^2 + (1.57079632n)^2\right]^{1/2} = 10/|X_c| \qquad (19)$$

The value of filter capacitance C can be found from equation (19) by considering L=0 and the value of C=8.876205198×10^{-4} F Similarly substituting the value of C in equation (19) the value of L=1.120814476mH for Single phase. Now by taking different values of Load parameters the value of L and C values can be easily calculated.

V. RESULTS AND DISCUSSION

The performance analysis of fixed and sinusoidal-band hysteresis current controller has been verified through MATLAB simulink environment and the simulation results are compared between them, with and without LC filters on the load side. The performance indices include THD level of three-phase load currents, current error minimization, average and maximum switching frequency and power factor of three-phase load. A fixed band controller will require a reference current signal, and upper and lower bands will be obtained by adding and subtracting the hysteresis band width respectively. A sinusoidal band controller will also require a reference current signal, and upper and lower bands will be obtained by increasing and decreasing the amplitude of the reference wave by the hysteresis band width respectively. Various R-L load, *R=3Ω and 2 Ω, L=5mH, 4mH and 3.5mH* are considered for simulation. A reference sine wave at 50 Hz and *±10A peak* , V_{dc}=*100 V* has been taken. The hysteresis band width is taken *±0.2A*.The THD level of three-phase load currents has been calculated using Fast Fourier Transform (FFT) technique and it could be analysis during load variations.

A. Performance Analysis without LC Filter Circuit

The actual current in hysteresis control is forced to tract the reference sine wave trajectory within the hysteresis-band. The reference and actual three-phase load current waveforms for fixed-band controller are shown in fig.7 (a,b) and we observed that, the actual current waveform is perfectly confined within upper and lower threshed levels of hysteresis-band. But it produces more current ripple than sinusoidal-band control scheme which is shown in the fig.7(c).The load current waveform contains some higher order harmonics and the corresponding THD level is nearly 2.08% without any low pass filter on the load side which is shown in fig.7 (d).

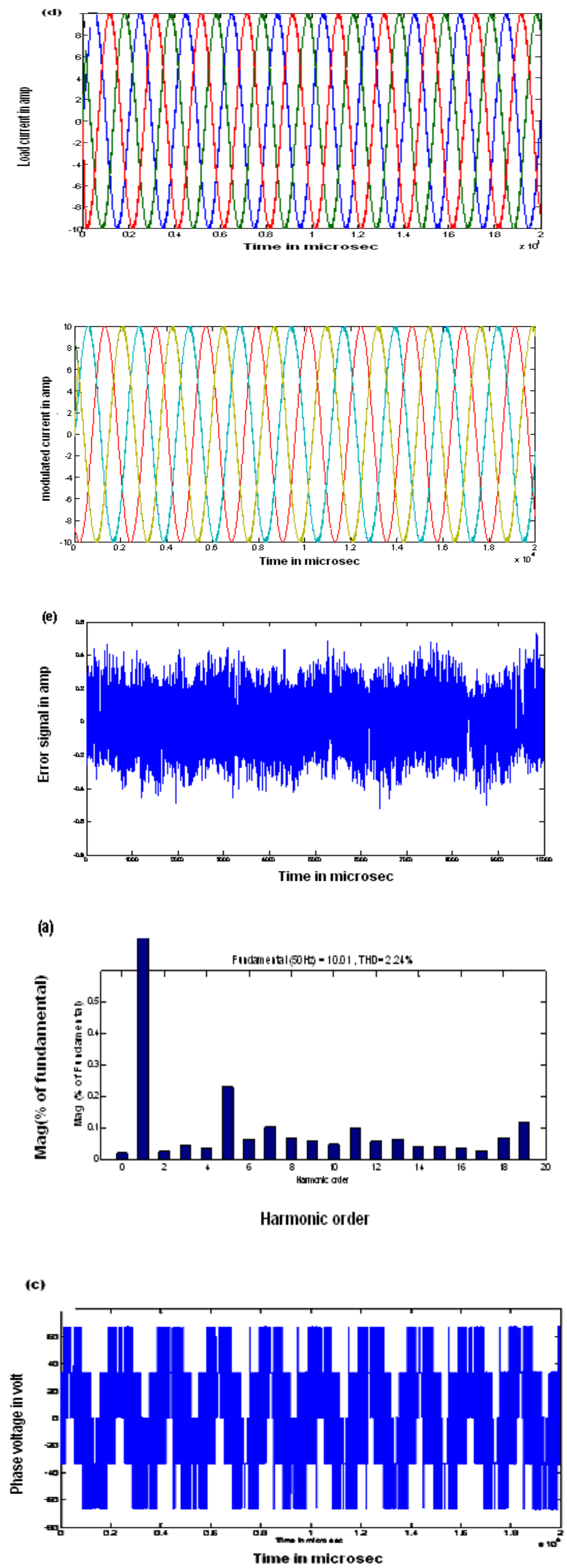
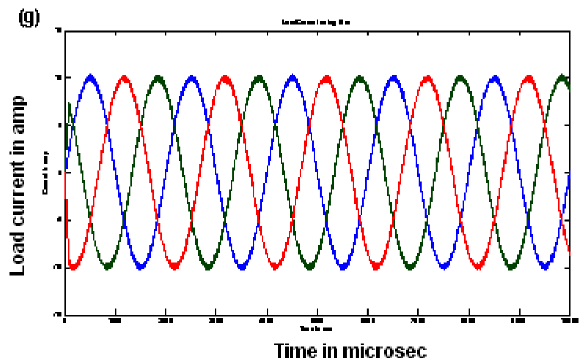
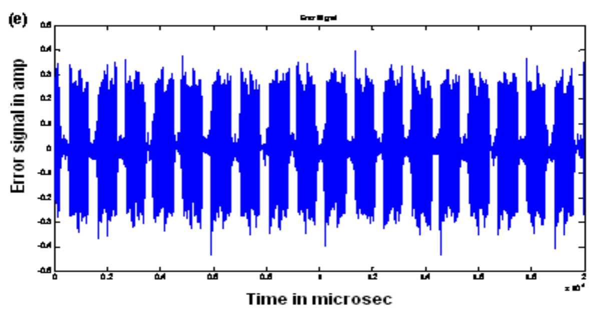
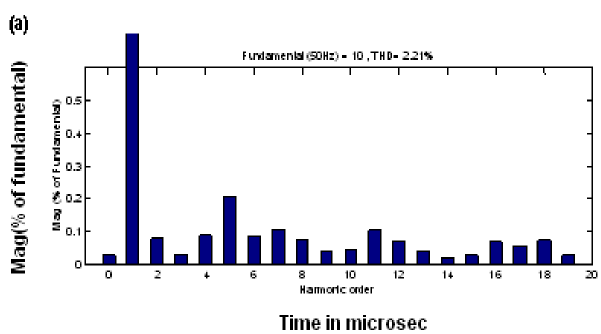


Fig.7. ±0.2A Fixed-band controller *(Load:R=3Ω,L=4mH)* without filter) (a) Reference current waveform (b) actual load current waveform (c) error signal (d) harmonic spectrum of load current (e) three-phase load voltage waveforms

Fig.7 (e) shows the corresponding three-phase inverter output voltage waveforms.The action of sinusoidal-band current controller has been graphically shown below, we observed that the load current is tracked with in sinusoidal band and it produces less current ripple compared to fixed-band control scheme. And resulting in less THD at the three-phase load currents







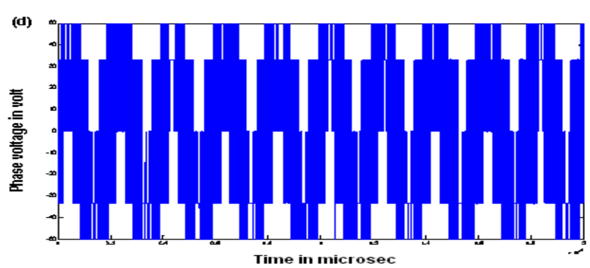
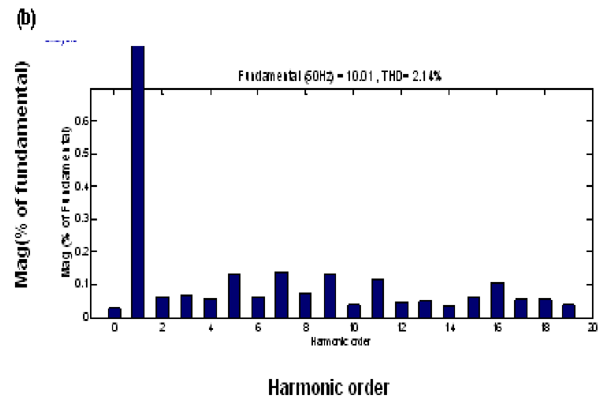


Fig.7. ±0.2A Sinusoidal-band controller*(Load:R=3Ω,L=4mH)* without filter) (a) actual load current waveform (b) error signal (c) harmonic spectrum of load current (d) three-phase load voltage waveforms

B. *Performance Analysis with LC Filter Circuit*

Both fixed and sinusoidal-band current controller based pwm voltage source inverter contains higher order harmonics. By incorporating LC filter circuit on the load side we can eliminate the harmonic content. For examine the LC filter on the load, following harmonic spectrum of load currents have been observed for both types of current controller which substantially having lower THD level.Fig.8 (a) and (b) depicts the harmonic spectrum of load three-phase load currents by fixed and sinusoidal-band current controllers with LC filter circuit. Table-1 shows the THD level of both fixed and sinusoidal-band current controller for different values of load parameters.



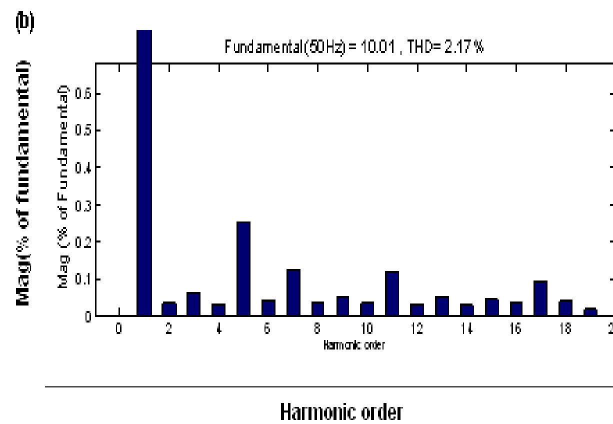


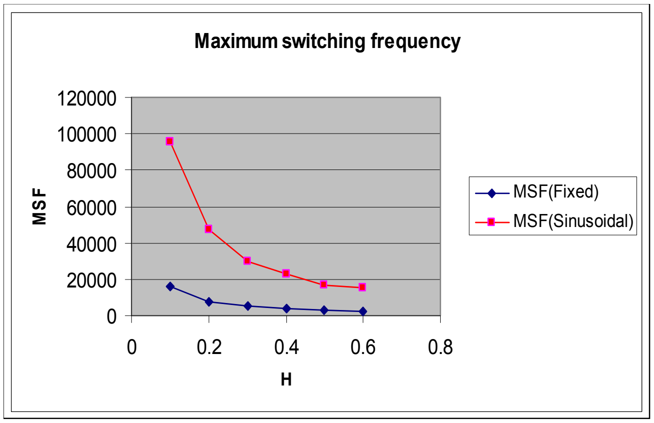
Fig.8. ±0.2A Fixed and Sinusoidal-band controller *(Load:R=3Ω,L=4mH)* with filter) (a) Harmonic spectrum of load current by fixed-band controller (b) Harmonic spectrum of load current by sinusoidal-band controller.

Table-I: THD level for both control schemes for different values of load parameters.

Load parameters	THD level by Fixed-band scheme (%)		THD level by Sinusoidal-band scheme (%)		Switching frequency (KHz)	
	Without Filter	With Filter	With out Filter	With Filter	Fixed-band scheme	Sinusoidal-band scheme
R=2Ω, L=3.5mH	2.63	2.60	2.60	2.54	1.942	1.95
R=3Ω, L=4mH	2.24	2.14	2.21	2.17	1.51	1.54
R=3Ω, L=5mH	2.08	2.01	2.03	2.00	1.845	1.885

C. *Maximum and Average Switching Frequency*

Fig.9 (a) (b) shows the variation of maximum and average switching frequency of both the current control scheme corresponding to the hysteresis band. The maximum and average switching frequency with the sinusoidal bands is higher than the corresponding fixed-band controllers.



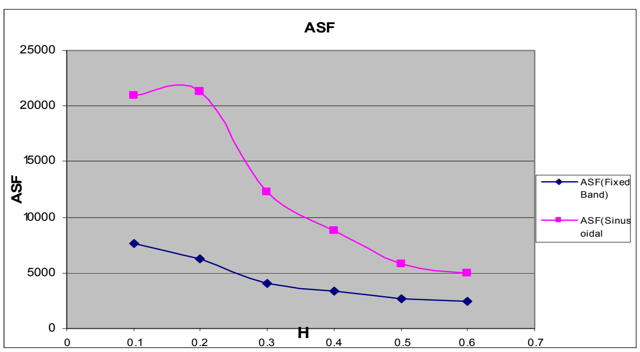


Fig.9. (a) (b) Maximum and Average switching frequency Variation corresponds to hysteresis band

VI. CONCLUSION

This paper described the current controlled PWM voltage source inverter with fixed and sinusoidal-band hysteresis controller in an instantaneous feedback loop. The behavior of the fixed and sinusoidal-band controller has been studied and its performance has been analyzed using MATLAB-Simulink environment. We observed that, with small (large) hysteresis width the sinusoidal waveform is confined within desired hysteresis band. At large hysteresis-band control the current is not confined with the sinusoidal waveform and both fixed and sinusoidal band controllers produces higher current ripple. The study also shows that a reasonable hysteresis-band, a sinusoidal band control results in a reduced ripple and lower harmonic content. Moreover, due to incorporating of LC filter on the load side higher order harmonic current contents could be eliminated and it gives lower values of THD.However, the average and maximum switching frequency is higher with sinusoidal bands. But this will not be the major concern with the availability of fast switching devices that can operate at lower switching frequencies on account of switching losses and reduced current ripple.

REFERENCES

[1] M.P.Kazmierkowaski, L.Malesani: “PWM Current Control Techniques of voltage source converters-A Survey” IEEE. Trans. On Industrial Electronics, Oct.1998.Vol.45, no.5, pp.691-703.

[2] D.M.Brod and W.Novotny, “Current Control of VSI-PWM Inverters”, *IEEEIIAS 1984 Annual Meeting,* 1984, pp.418-425.

[3] M.Azizur Rahman, Ali M. Osheiba. “Analysis of current controllers for voltage-source inverter” IEEE Transaction on industrial electronics, Aug-1997vol.44, no.4, pp.477-485.

[4] A. Tripathi, P.C.Sen, “Comparative analysis of fixed and sinusoidal band Hysteresis current controllers for voltage source inverters”, IEEE Trans.on Industrial Electronics, Feb-1992, Vol.39, N0.1, pp.63-73.

[5] Luigi Malesani and Paolo Thnti “A Novel Hysteresis Control Method for Current-Controlled Voltage-Source PWM Inverters with Constant Modulation Frequency”, IEEE Transactions on Industrial Applications, Jan-1990, pp.88-92.

[6] B.K.Bose, “An Adaptive Hysteresis-Band Current Control Technique of a Voltage Fed PWM Inverter for Machine Drive System”, *IECON 1988*, pp.684-690.

[7] Simone Buso and Luigi Malesani, “Comparison of Current Control Techniques for Active Filter Applications”, IEEE Transactions on Industrial Electronics, Oct-1998. Vol.45, pp.722-729.

[8] K.M.Rahman, M.R.Khan, M.A.Choudary and M.A.Rahman, “Variable-Band Hysteresis Current Controllers for PWM Voltage Source Inverters”, IEEE Transactions on Power Electronics, Nov-1997,Vol.12, No.6,pp.964-970.

[9] S.Ogasawara, H.Akagi and A.Nabae: “A Novel PWM Scheme of Voltage Source Inverter based on Space Vector Theory”. Proceedings of European conference on power Electronics Applications, EPE-89, Aachen, Oct.1989, pp.1197-1202.

[10] B.Vasantha Reddy**,** B Chitti Babu “ Hysteresis Controller & Delta Modulator-A Two viable scheme for Current Controlled Voltage Source Inverter”, Proceedings of IEEE International Conference on Technical Postgraduates 2009, TECHPOS 2009, Malaysia, pp.01-06.