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Improving Switching Frequency Variation of Hysteresis Current Controlled VSI Fed Induction Motor Drive

By

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Abstract:

Switching frequency variation over the entire operating speed range of an induction motor (IM) drive is the major problem associated with conventional two-level three-phase hysteresis controller as well as the space phasor based pulse width modulation (PWM) hysteresis controller. This paper presents a new variable band hysteresis current controller for controlling the switching frequency variation in the two-level PWM inverter fed IM drives for various operating speeds. A novel concept of online variation of the band based on both the instantaneous load current and current change for each sampling period is presented to determine the hysteresis band. A performance comparison of the proposed with conventional hysteresis current controller for IMdrive is provided in simulation. The proposed drive system is also implemented in real-time using DSP board DS1104 for a laboratory 1.5 hp motor. Comparative simulation and real-time results verify the feasibility of the proposed scheme and demonstrate that the proposed method has obtained constant switching frequency and improved the performance of the drive system.

Keywords:

Switching frequency, Hysteresis current controller (HCC), Induction motor (IM),

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1. Introduction:

Voltage source inverters (VSI) used for generating sinusoidal fundamental voltage with variable frequency and voltage can be either voltage controlled or current controlled [1–5]. Current controlled VSIs are extensively employed in High Performance Drives because of the considerable advantages offered by them as compared to the voltage controlled VSIs[1]-[3]. The quality of the applied current controller greatly influences the overall control system performance. Therefore, over the past few decades, considerable research has been done on current control techniques, and from this work three major classes of current controller have evolved: predictive controllers, linear proportional–integral (PI) controllers, and hysteresis controllers [3]-[4]. Predictive controllers are the most complex method and require the knowledge of load parameters. Extensive hardware implementation is another disadvantage of this technique. Linear PI current controller can limit the switching frequency of the inverter and produce a well-defined harmonic content. However, parameters of PI controllers must be carefully tuned with a tradeoff between maintaining the system stability over the whole operation range and achieving an adequate dynamic response during transients [3,5]. While, HCC have been widely used because of the noncomplex implementation, outstanding stability, absence of any tracking error, very fast transient response, inherent limited maximum current, and intrinsic robustness to load parameters variations [3]-[6].

However, the conventional type of hysteresis controllers suffers from drawbacks, e.g. limit cycle oscillations, Occasional hysteresis band violation up to twice the permitted bandwidth , generation of sub-harmonic components in the current and random (non-optimum) switching [4,6,8-9]. To eliminate these basic drawbacks, different types of fixed tolerance bands (hexagonal, circular, rectangular, etc., [8]) of current error space phasor based hysteresis controllers are reported in the literature [3], [6]–[8], [9]–[13]. However, the common problems associated with the conventional fixed band hysteresis controllers are the variation of switching frequency in the fundamental output cycle and variation of switching frequency with the variation in the speed of the load motor [13]-[17].

Variable switching frequency causes three main problems: High total harmonic distortion (THD) in the load current and this causes overheated machines and hamper the design of low order harmonic filters; increases the interference between phases (in three phase systems) in case of isolated neutral or delta connected systems as a result the current error increases and can reach twice the hysteresis band; and irregularity of modulation pulses which causes a torque ripple that result in speed oscillation and mechanical vibration. These problems reduce the drive performances. Several methods have been presented to address these problems.

An adaptive hysteresis band current control technique presented in [14] programmes the hysteresis band (individual band for each phase of machine) as a function of load and supply parameters to optimize the PWM performance.

A sinusoidal band hysteresis current controller, proposed in [15], leads to the higher average switching frequency compared to the corresponding fixed band hysteresis controller and hence demands for proper lockout of the switching frequency, which may cause current distortion. A combination of mixed-band (sinusoidal band added to a fixed band) and equidistant-band hysteresis current controllers is emphasized in [18], which eliminates the additional lockout circuits. Another alternative for the variable band hysteresis controller suggested in [19] uses complex feedback and feed forward control blocks. In an adaptive hysteresis band current control strategy proposed in [20], the hysteresis band equation is derived as a function of q-axis reference current (variations of load), speed and neutral voltage of the motor in order to hold the switching frequency constant. Hysteresis current controller (HCC) for the PWM rectifier proposed in [22, 23] does not prevent the variation in switching frequency for the entire operating speed range of the motor. Modular hysteresis controller for multi-level inverters is proposed in [24]. It does not discuss about the switching frequency variations.

A digital predictive hysteresis controller has been proposed to remove these problems [25]. This method gives a very satisfactory transient and steady-state performance, but still requires complex online computations. However, the band control schemes presented in [14-15] and [18-21] are either complex to implement, requires extensive knowledge of the system parameters, suffer from the stability problems, or have limitations in transient performance. Also, more importantly, though in [14-15] and [18-21] the efforts are made to control the switching frequency in a fundamental cycle, however, the variation of switching frequency over various operating speed ranges of the machine is not examined.

In [26], a continuously varying parabolic boundary for the current error space vectoris proposed to get the switching frequency variation pattern of the output voltage of the HCC-based PWM inverter similar to that of voltage-controlled space vector PWM-based VSI. But the major problem associated with this technique is the requirement of extra outer parabola for the identification of sector change which gives rise to some switching frequency variations in one fundamental cycle and over the entire operating speed range. It also introduces fifth and seventh harmonic components in the voltage causing fifth and seventh harmonic currents in the induction motor. These harmonic currents may cause sixth harmonic torque pulsations in the machine, especially in low speed operation.

This paper describes a new simple variable band HCC for controlling the switching frequency variation in the two-level PWM inverter fed IM drives. A novel concept of continuously varying the hysteresis band for the controller is suggested in order to insure a constant switching frequency. The proposed method retains all advantages of the conventional HCC. Furthermore, the current error, torque oscillation, and load current THD are decreased very effectively. To verify the feasibility of the proposed scheme, computer simulations and experiment results are presented.

2. New variable band hysteresis current control scheme

The predictive hysteresis-band current control scheme is suggested to achieve constant switching frequency and more precise current control with minimum harmonic distortion.The design of this predictive hysteresis-band current controller depends on two main parameters one of them is the value of the instantaneous current at a certain time or a certain period (n, n-1) and the second is the value of the current change during this period. Then, the algorithm uses the results of previous switching cycles to forward estimate the future load current.

The basic variable band current control scheme is shown in Fig. 1. In this scheme, the actual load currents are sampled and the corresponding current changes are calculated for each motor phase, for each sampling instant, and hence the band can be obtained as follow:

$$H_a(n) = k_1 i_a(n) + k_2 \Delta i_a(n). \quad (1)$$

$$\Delta i_a(n) = i_a(n) - i_a(n-1). \quad (2)$$

Where H_a (n) is the phase "a" band at n-th sampling instant, i_a (n) is the phase "a" motor current at n-th sampling instant, Δi_a (n) phase "a" current change at n-th sampling instant and i_a(n-1) is phase "a" current at (n-1) th sampling instant, Where K_1 and K_2 are constants and these constants are calculated by trial and error methods in this paper.

We notice from "(1)," and "(2)," that at each sampling period the band is updated according to the value of the actual load current and the current change. Based on this new band, reference current and actual current the inverter switching action is generated and the actual load currents follow the reference ones. By developing this new online variable band, the inverter switching frequency is maintained constant as we will indicate in the experimental results.

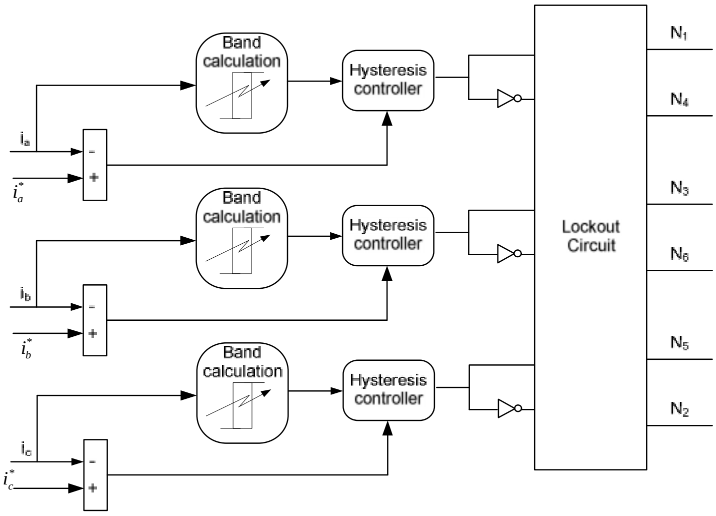


Fig.1 The proposed variable band HCC scheme

3. Simulation Results

Simulation studies are carried out in two main directions: verifying the validity of the proposed current controller for induction motor drive fed with VSI based IFOC for different operating speeds and comparing its performance with the conventional fixed band hysteresis current controller. So The complete drive system shown in Fig. 2 is simulated in MATLAB/Simulink first with parameters given in Appendix I, then a detailed simulation study of both the conventional fixed band HCC scheme and the proposed NVBHCC scheme are carried out, here are some of these results.

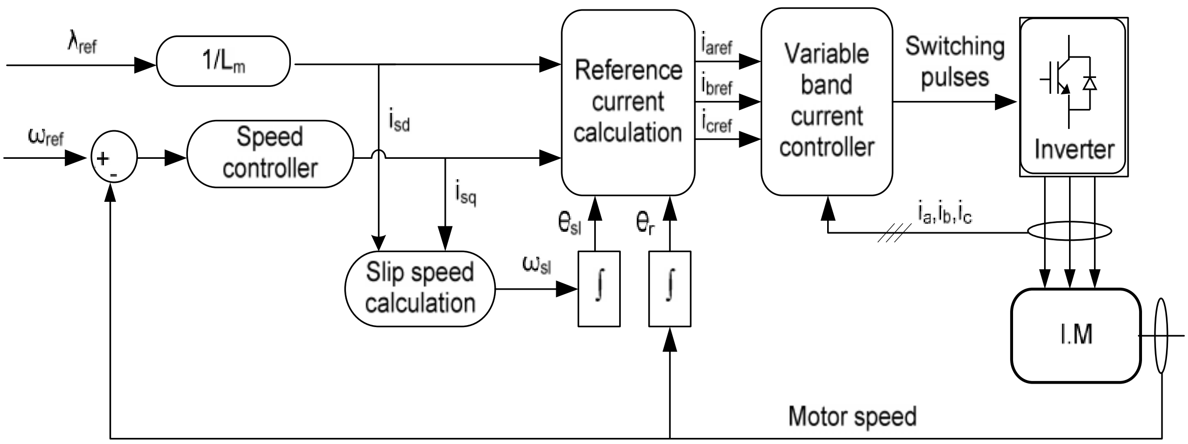


Fig.2 The proposed current controller for IM drive

Figs. 3(a)-(d) show phase "a" motor current , its corresponding fast fourier transform (FFT) analysis, the developed torque, and stator flux linkage locus respectively in steady state operation for fixed band HCC for 1500 rpm speed command at rated load (7.5 Nm) conditions.

As seen from the above figures, one can notice that the stator current is nearly sinus curve, and the motor current follows the the reference one with a total harmonic distorsion of 5.117 % .
It can be noticed that the mean value of torque (T_m) is 7.4994 Nm and the torque oscillation amplitude (T_{osci}) is 1.1166 Nm. these correospod to 0.0082 % torque static error (T_{err}%) and 14.8875 % oscillation torque (T_{osc} %). While the flux linkage static error (F_{err}%) and flux linkage oscillation (F_{osc} %) values are 2.9535 % and 2.6393 % respectively.

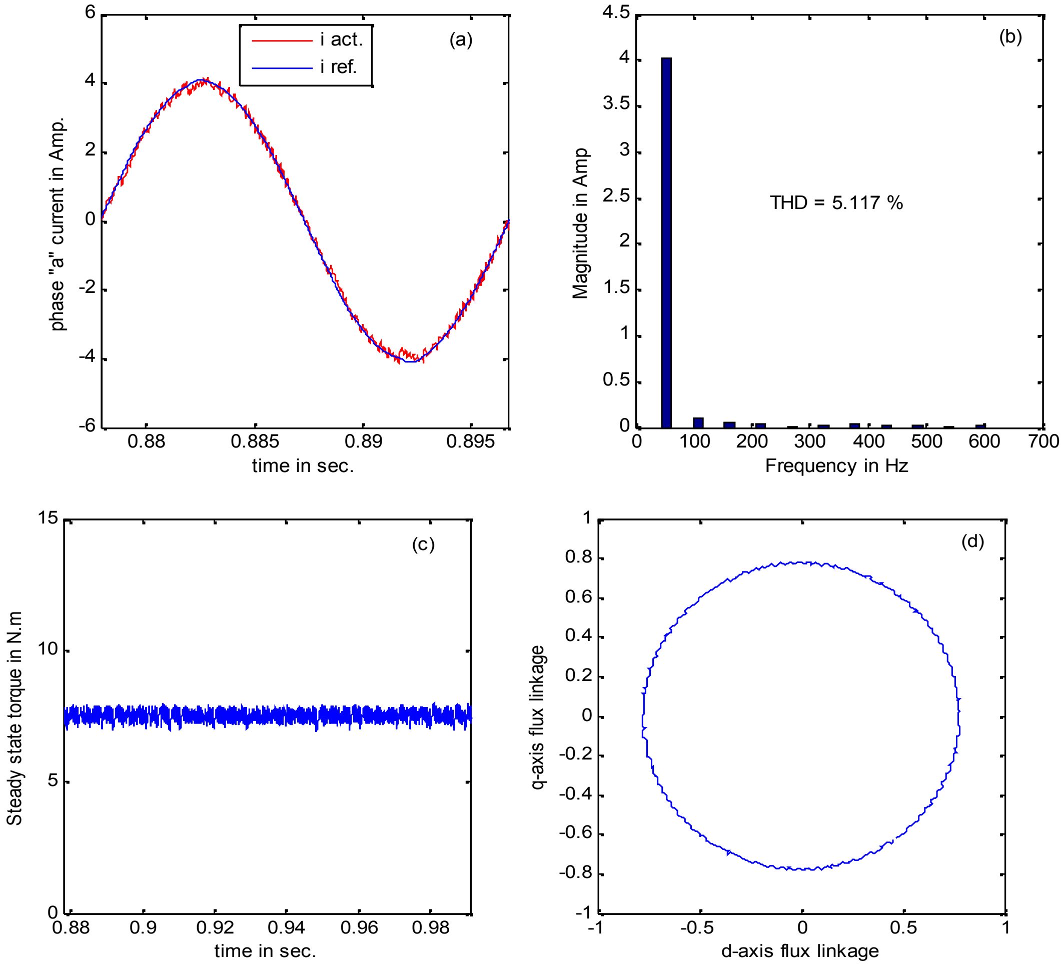


Fig. 3 Steady state drive responses for fixed band HCC at full load and 1500 rpm speed command conditions

The corresponding drive responses at the same operating conditions for the proposed NVB controller are shown in Figs. 4(a) – (d), respectively.

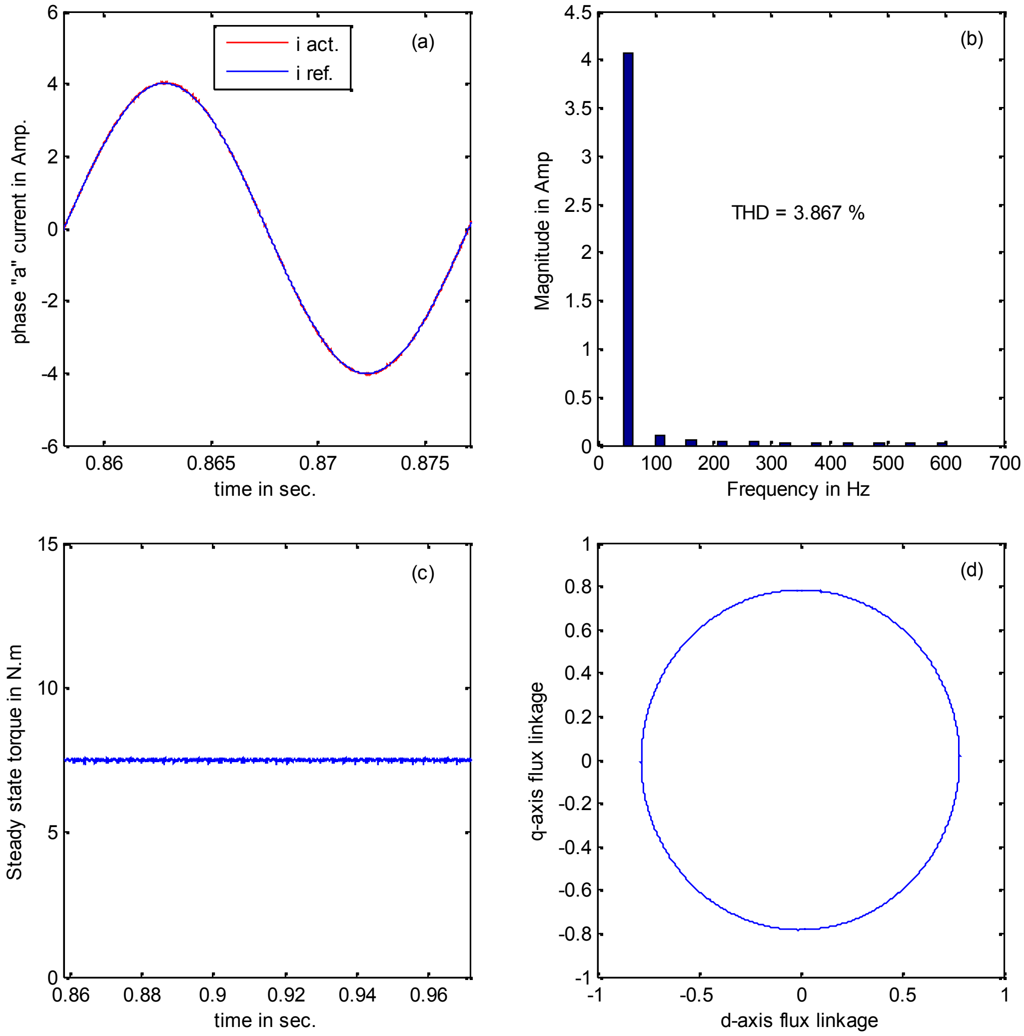


Fig. 4 Steady state drive responses for NVBHCC at full load and 1500 rpm speed command conditions

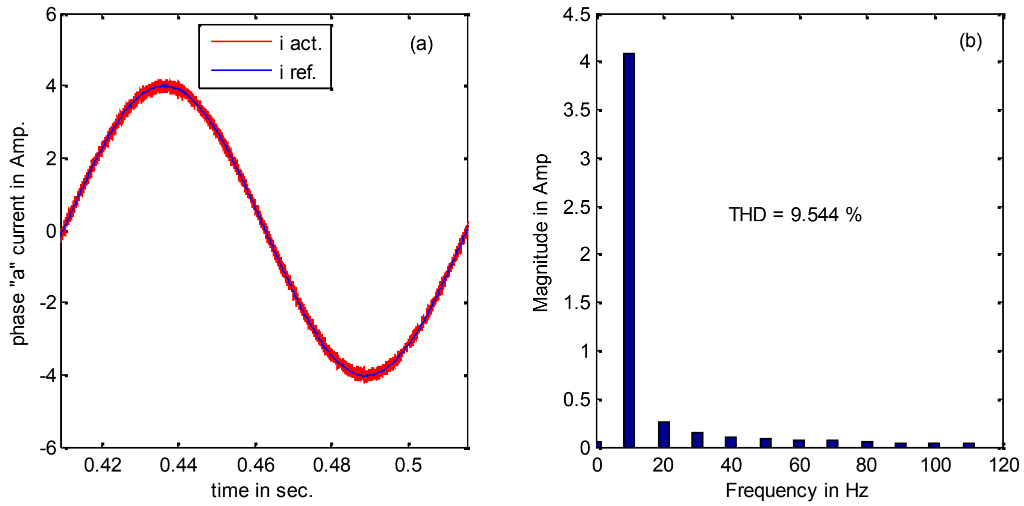
As seen from the above figures, one can notice that the stator current is very close to sinus curve, and the motor current follows the the reference one with a total harmonic distorsion of 3.867 % . Table 1 summerizes the drive steady state performances at these operating conditions for both fixed and the proposed control schemes.

Table 1.
Drive steady state response at high speed & full load condition

Method	THD %	T_{osc} %	F_{osc} %
Fixed band	5.117	14.88	2.63
Proposed	3.867	3.3269	0.4772

Fig. 3 and Table 1 prove that the load current contains high THD for the fixed band HCC due to variable switching frequency nature of the controller and this affects greatly both the flux and the developed torque of the motor. While in Fig. 4 and Table 1, the NVBHCC results prove the fact that this method has worked properly results in fixing switching frequency. This result decreases the load current THD, consequently, it reduces the flux and developed torque oscillations of the IM.

The corresponding drive responses at 200 rpm speed command at rated load (7.5 Nm) conditions for both the fixed band and NVBHCC schemesr are shown in Figs. 5(a) – (d), and fig. 6(a)–(d), respectively. Table 2 summerizes the drive steady state performances at these operating conditions for both control schemes.



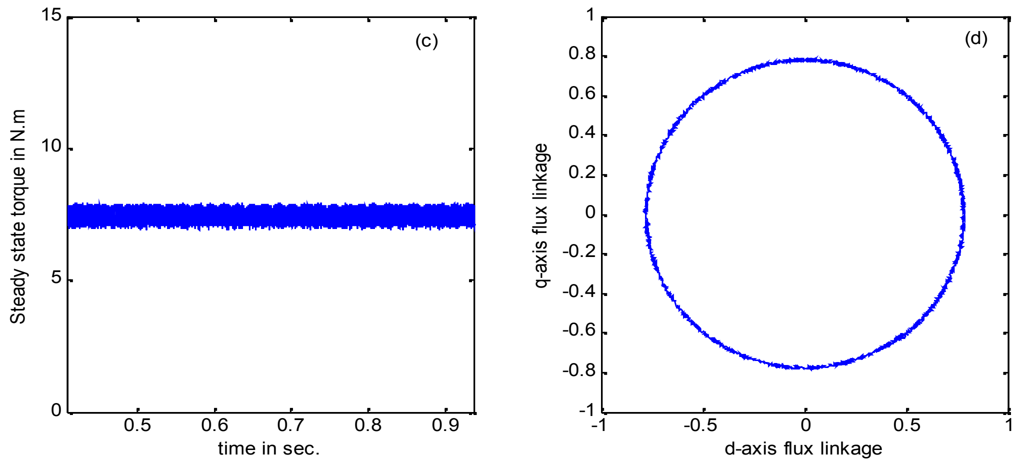


Fig. 5 Steady state drive responses for fixed band HCC at full load and 200 rpm speed command conditions

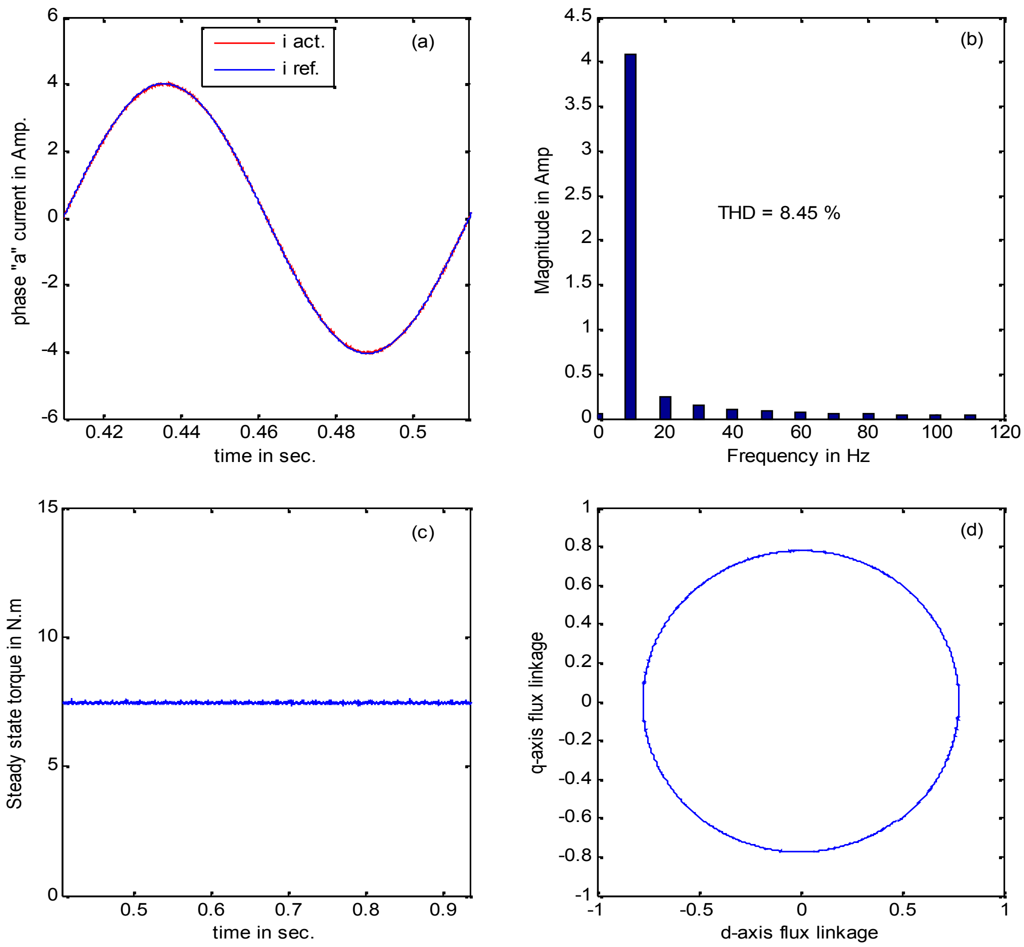


Fig. 6 Steady state drive responses for NVBHCC at full load and 200 rpm speed command conditions

Table2.
Driveresponse at low speed & full load condition

Method	THD %	Tosc %	Fosc %
Fixed band	9.665	14.206	3.432
Proposed	8.69	3.793	1.4119

Although, As previously shown, the drive performance for both fixed band and NVBHCC is greatly affected in low speed operation. it is clear that, the proposed scheme gives better performance than the conventional fixed band control scheme.

4. EXPERIMENTAL VERIFICATION

The investigated fixed band HCC and the proposed NVBHCC have been tested in a laboratory setup to verify the simulation results and to verify the robustness of the proposed current control scheme.

A. *LABORATORY DRIVE SETUP*

The proposed IM drive has been simulated with Matlab/Simulink and then experimentally implemented using dSPACE DSP board DS1104 for a laboratory 1.5 hp IM. A close snap shot of the experimental IM drive setup for the proposed scheme is shown in Fig. 7 and hardware schematic diagram for real time implementation is shown in Fig. 8. The DSP board DS1104 [28] is installed inside a personal computer with uninterrupted communication capability through a dual port memory. The DS1104 board is mainly based on a 64-bit PowerPC type PPC603e processor. This processor operates at the clock frequency of 250 MHz with 32 kB cache memory. This board has a 32 MB of SDRAM global memory and 8 MB of flash memory.

Fig. 7. A snap shot of the experimental setup.

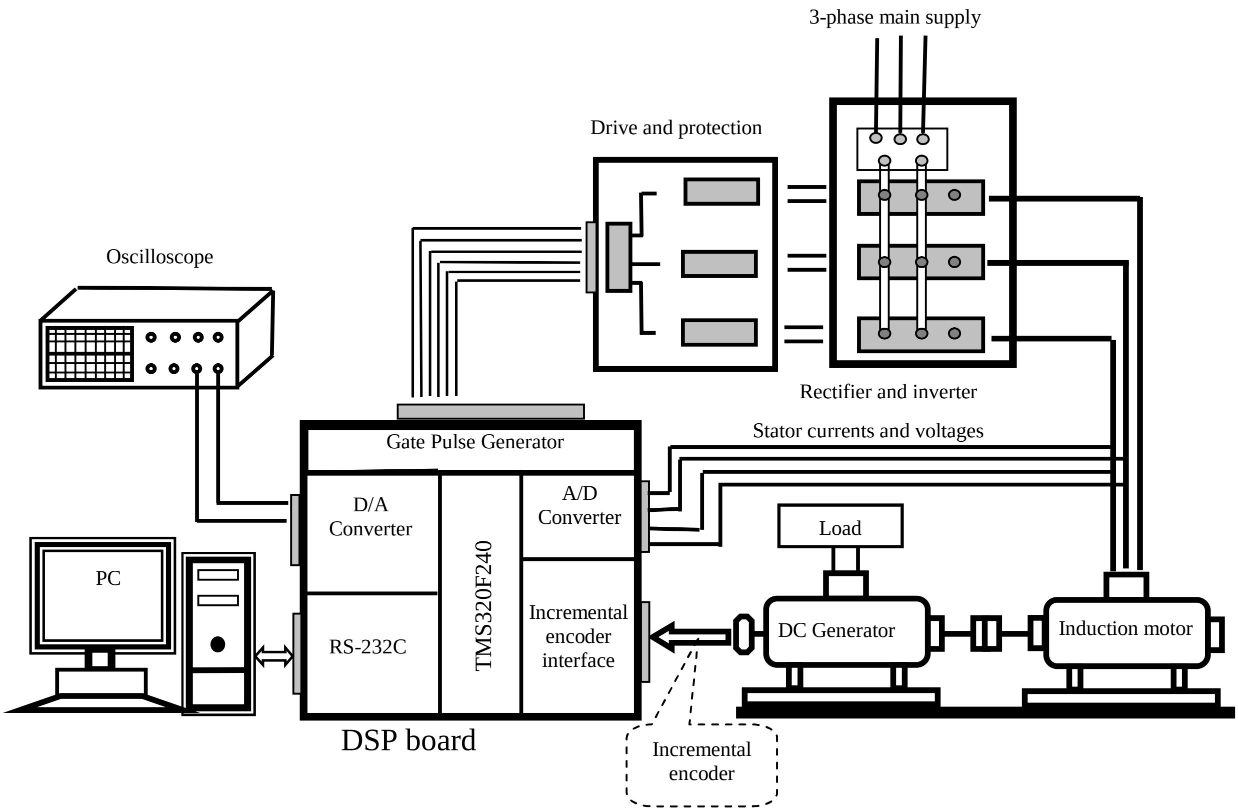


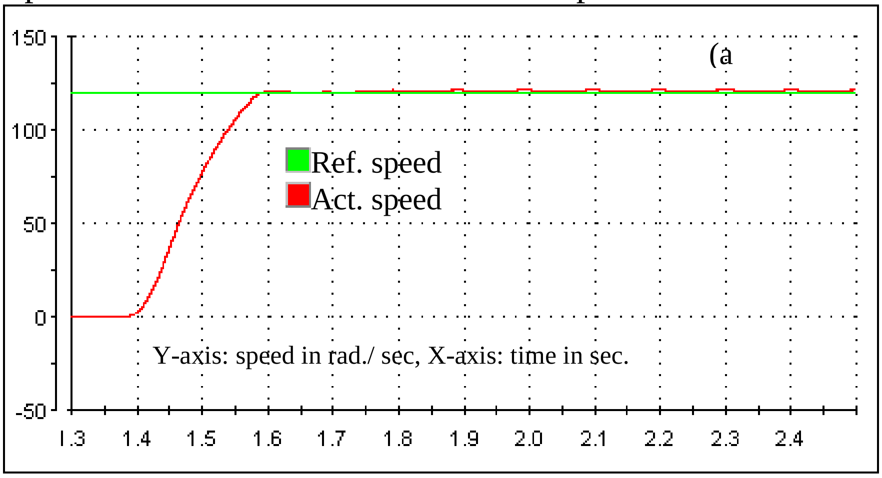
Fig. 8 Hardware schematic for real time implementation of IM drive

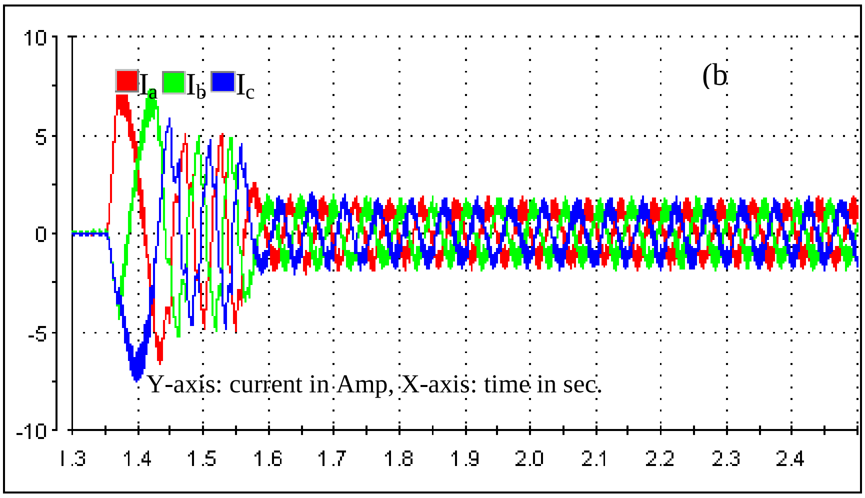
The DSP is supplemented by a set of on-board peripherals used in digital control systems including analog to digital (A/D), digital to analog (D/A) converters and digital incremental encoder interfaces. This board is also equipped with a Texas Instruments TMS320F240 16-bit micro controller DSP that acts as a slave processor and provides the necessary digital I/O ports and timer function such as input capture, output capture and PWM generation. The PC based controller generates numerical switching commands to the DSP board whereas the outputs of the DSP board are sent to the base drive circuit to drive the VSI inverter. The motor current is measured by the Hall-effect sensors, which is fed back to the DSP board through the A/D channels. A speed encoder supplying 1024 pulses/revolution is used for speed feedback. to the DSP board through an encoder interface. The tested IM is coupled to a dc machine which is operated as a generator in order to adjust the mechanical load to the tested motor. For real-time implementation, a real-time Simulink model is developed and then downloaded to the DSP board utilizing dSPACE ControlDesk software. The command phase currents i_a^*, i_b^* and i_c^* are generated from i_q^* and i_d^*. The HC compares the actual phase currents with corresponding command phase currents to generate appropriate PWM logic signals.

These signals trigger the IGBT gates of the inverter in order to supply the appropriate voltage and frequency to the motor. The sampling frequency used in the work is found to be 10 kHz.

B. EXPERIMENTAL RESULTS

Numerous experimental tests have been completed to evaluate the performance of both current control schemes at various operating conditions. Some sample results have been presented in this section. Figs. 9(a) - (c), and 10(a) – (c) show the speed response, stator currents and phase 'a' actual and command current responses of the drive for both fixed band and the proposed current control schemes respectively at a 120 rad/sec speed command and no load conditions. These figures reveal that the proposed control scheme has actual current tracking to the reference one with high accuracy and satisfactory speed response performance in addition to balanced operation of the motor.





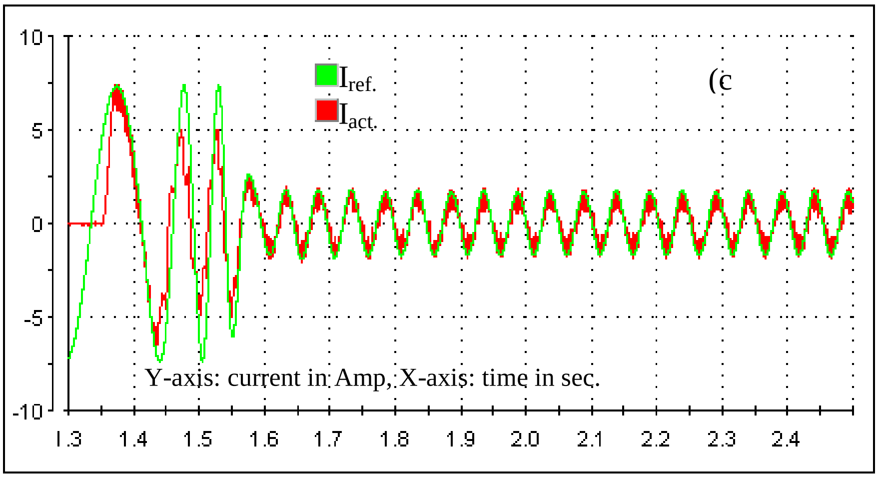
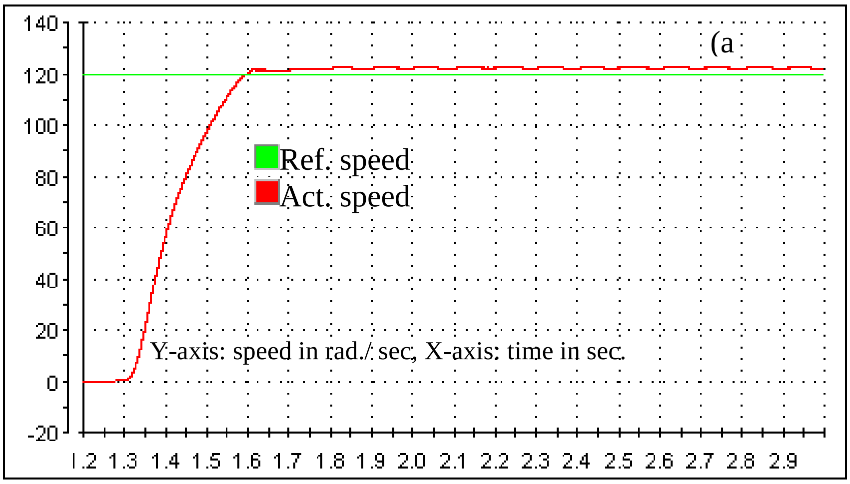
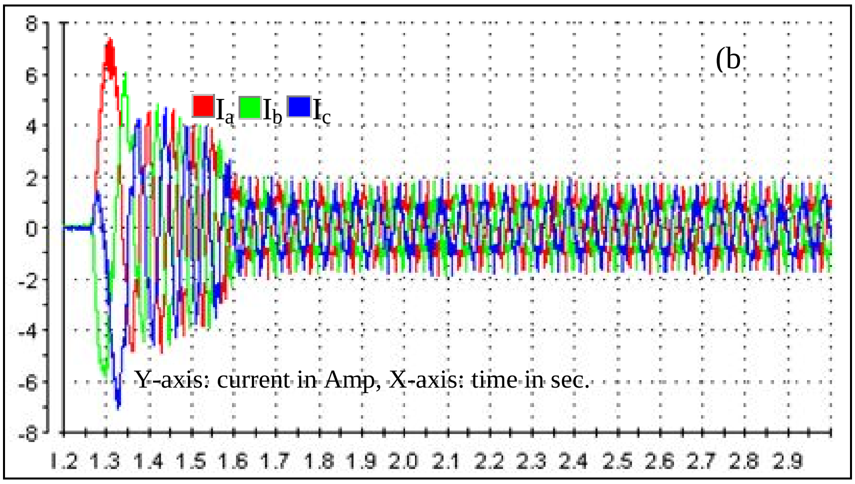


Fig.9 Experimental drive responses for fixed band HCC at no load and a speed command of 120 rad/sec





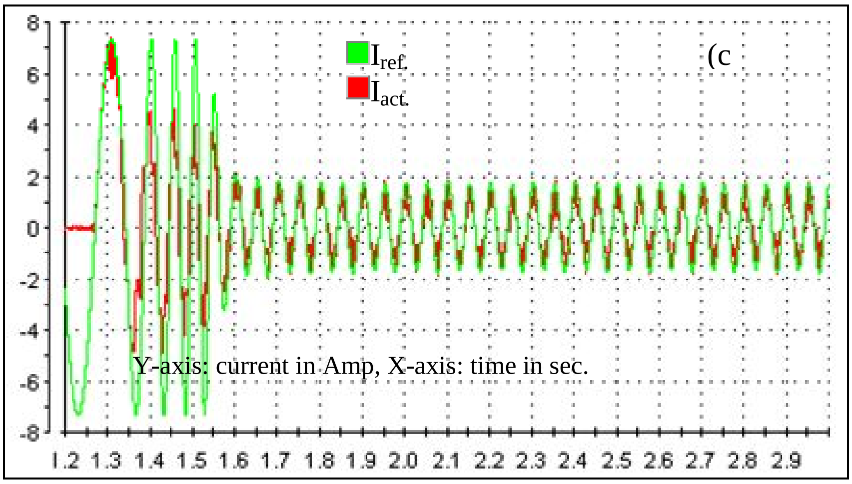


Fig.10 Experimental drive responses for the NVBHCC at no load and a speed command of 120 rad/sec

Figs. 11 and 12 show the instantaneous switching frequency for the fixed-band HCC and the NVBHCC respectively. It is obvious that the switching frequency in fixed-band HCC varies in vast range . It changed from a minimum ($f_{sw,min}$) value of 149 Hz to a maximum ($f_{sw,max}$) value of 1250 KHz while the average switching frequency ($f_{sw,ave}$) is 458 Hz and cause audio noises and inject high frequency components in the load current that makes it difficult to design appropriate filters for eliminating them. while, the NVBHCC results prove the fact that this method has worked properly results in fixing switching frequency, where the variation range of switching frequency has been limited to small domain ($f_{sw,min}$ = 476 Hz to $f_{sw,max}$ = 833 Hz, while $f_{sw,ave}$=614 Hz). As the variable switching frequency cause audio noises, the proposed cc scheme fixes this problem by constant switching frequency, too.

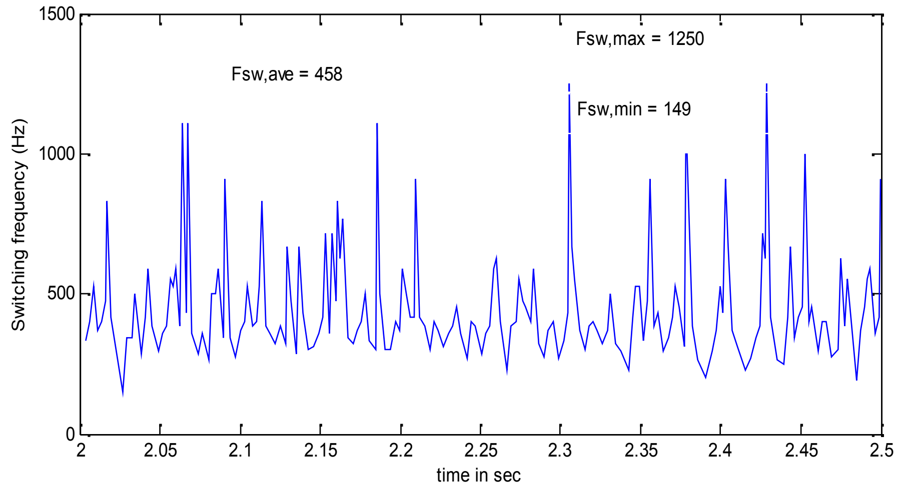


Fig. 11 Instantaneous switching frequency for fixed-band HCC

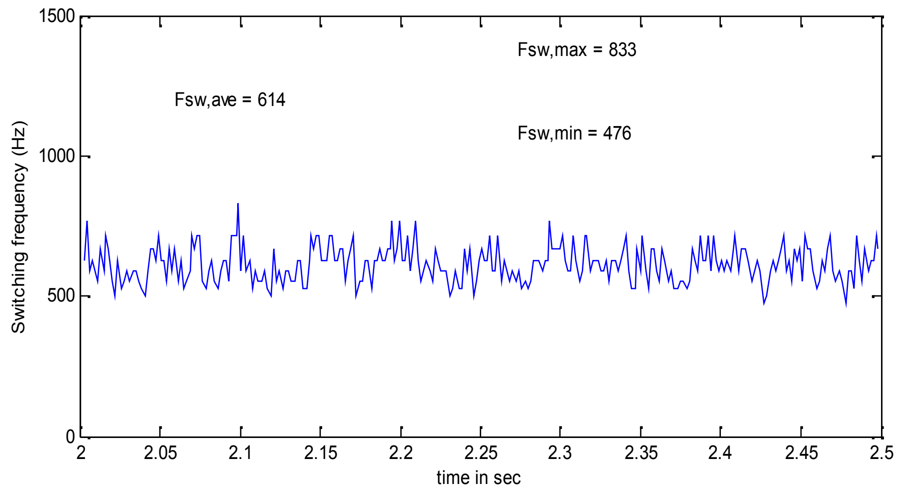


Fig. 12 Instantaneous switching frequency for NVBHCC

5. Conclusion

In this paper, A new concept of online variation of hysteresis band is proposed to control the switching frequency variation in hysteresis controller-based two-level PWM inverter fed IM drives. At each instant, the hysteresis band is updated based on the instantaneous load current and current change. The suggested digital adaptive hysteresis current control is shown to be particularly simple and effective in achieving constant switching frequency, moreover, the speed response, motor current THD, developed torque and flux ripples of the proposed scheme are better than those of the conventional fixed band PWM-HC control method. The proposed IM drive has been successfully implemented in real-time using DSP board DS1104 for a laboratory 1.5 hp motor. Several simulation and experimental results are provided to demonstrate the superior performance of the proposed current control scheme over conventional fixed band HCC for IM drive over the entire operating speed range.

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Appendix

Induction motor parameters:
1.5 kW, three phase, rated voltage: 380 V line to line, 50 Hz, rated speed: 1400 rpm, four poles,
R_s = 7.4826 Ω, R_r = 3.684 Ω, L_s = L_r = 0.4335 H, and L_m = 0.4114 H