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Three-level Hysteresis Current Control for a Three-Phase Permanent Magnet Synchronous Motor Drive

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***Abstract*—This paper presents a novel three-level hysteresis current control scheme for a three-phase permanent magnet synchronous motor (PMSM) fed by two single-phase four-switch voltage source inverters. Based on two-level hysteresis current control techniques for a single-phase four-switch inverter, a novel three-level PWM method for three-phase PMSM motor is implemented to reduce the magnitude and variation of the switching frequency. To obtain better harmonic performance, an improved variable band hysteresis method for three-level three-phase voltage source inverter is further proposed. Considering three states of output average voltage of the inverter, a new hysteresis controller with variable band calculated by the motor resistance, inductance, DC-link voltage, phase current and back-emf is designed to maintain constant phase leg switching frequencies. The proposed method is simple and effective, and verified by the simulation.**

Keywords-permanent magnet synchronous motor; current hysteresis control; eight-switch inverter

I. Introduction

Current regulation of an AC motor drive is now the de-facto standard for speed as well as torque control. Two general methods are used consisting of “sine-triangle” or space vector based chopper control and hysteresis control. From the view of the output switching frequency, the latter can be treated as a variable frequency method and the former a fixed frequency approach [1]. In low performance applications of motor drives with six-switch inverter shown in figure 1, hysteresis control is the favorite solution with simple and fast realization and inherent peak current limiting capability under two-level modulation. However, its drawback of variable switching frequency limits its wide application. In recent years, investigations have progressed to improve the control performance of the traditional two-level hysteresis regulator [2]. It is well known that the harmonic performance of two-level modulation is greatly inferior to three-level modulation. However, for a six switch, three-phase voltage source inverter, two-level modulation is generally only possible. To employ three level modulation with a three phase motor requires the use of 12 switches making the approach relatively costly [4].

This paper presents a novel hysteresis current control scheme with three-level modulation and variable hysteresis band for three-phase PMSM drives. Two single-phase four-switch voltage source inverters fed to the PMSM have three phase voltage output modes of positive voltage, negative voltage and zero voltage. By the analysis of traditional two-level modulation for a hysteresis current controller and voltage modes of a single-phase four-switch inverter, a zero-voltage mode is introduced in the proposed controller to achieve three-level current modulation for three-phase PMSM drives. Also, to reduce the variation of the switching frequency, a variable band scheme for the three-level hysteresis current controller is presented. The result achieves a substantial reduction in the current error and torque ripple as well as the variation of the switching frequency, while retaining all of the advantages identified with traditional hysteresis current control. The proposed scheme has been verified by detailed simulation results.

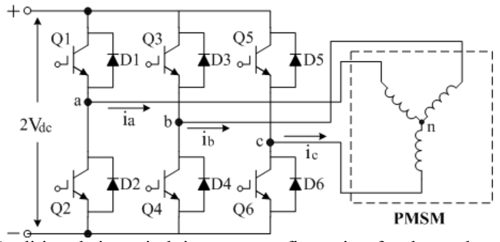


Fig. 1. Traditional six-switch inverter configuration for three-phase PMSM drive under two-level modulation

II. Two- Phase Eight-Switch Inverter

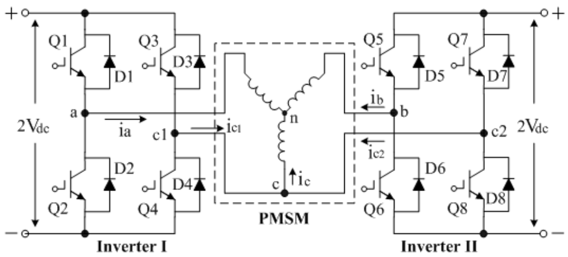


Fig. 2. Proposed eight-switch inverter configuration for three-phase PMSM drive under three-level modulation

For traditional three-phase PMSM with a star-type winding connection, the currents of the three phase windings are expressed as ia+ib+ic=0. Subsequently, it is known that if any two phase currents are controlled to their reference values, the third one inherently has a 120 electrical degree phase shift with respect to the other two. Using this consideration, a novel drive scheme for three-phase PMSM is proposed to realize current hysteresis regulator of three-level modulation. As shown in figure 2, a traditional three-phase PMSM with sinusoidal back-EMF is supplied by two single-phase four-switch inverters of the inverter I and II shown in the figure 1. Four inverter legs are formed by eight switches (Q_i, i=1, 2, … ,7 ,8) and its anti-parallel diodes (D_i, i=1, 2, … ,7 ,8). Three ends (a, b and c) of three motor windings (an, bn and cn) are respectively connected to the neural points of four inverter legs fed by two independent DC power sources. With the proposed inverter topology for three-phase PMSM drives, if two phase current of ia and ib is controlled to their values, ic inherently achieves 120 electrical degree phase for the normal operation of three-phase PMSM. In one of two single-phase inverters, there are three switching modes of four switches for the proposed three-level current hysteresis regulator, shown in the figure 3.

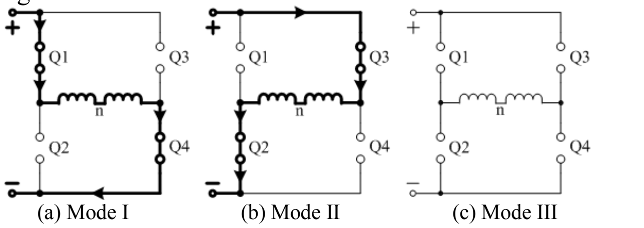


Fig. 3. Three operation modes of one phase inverter

In mode I of the figure 3(a), positive phase voltage is fed to two windings while Q1 and Q4 switch on and Q2 and Q3 switched off. In mode II of the figure 3(b), negative phase voltage is fed to the windings while Q2 and Q3 switch on and Q1 and Q4 switches off. The mode III of the figure 3(c) are the state of zero phase voltage in the winding, which are also used as the freewheeling channel for the winding currents of Mode I or II.

For a two-level hysteresis regulator of a three-phase PMSM fed by six-switch inverter of figure 1 or eight-switch inverter of figure 2, only Modes I and II are used to generate two-level phase inverter outputs with positive and negative voltage levels. However, for three-level hysteresis operation, Mode III is introduced to generate the third level in the windings while Mode I and II are used to generate positive and negative inverter voltage outputs. Based on the proposed inverter topology for three-phase PMSM drive of the figure 2, three-level voltage modulation for the current hysteresis regulator are investigated in the paper to achieve better harmonic performance. Meanwhile, to keep the constant frequency of the output voltage of the inverter, a variable band scheme for the hysteresis regulator under three-level modulation is illustrated in the following sectors.

III. PROPOSED THEE-LEVEL HYSTERESIS CONTROLLER WITH VARIABLE BAND

A. *Traditional two-level hysteresis regulator with variable band*

In the hysteresis operation with two-level modulation, the waveforms of phase current error, phase voltage output and PWM pattern are give in the figure 4. B is the tolerance of the hysteresis. The operation in one period contains two steps of positive and negative voltage outputs with the operating times of T_1 and T_2 respectively. As shown in the figure 4, when the current error reaches the outer hysteresis boundary, the inverter is set to a positive or negative voltage level which makes the current error change in the opposite direction.

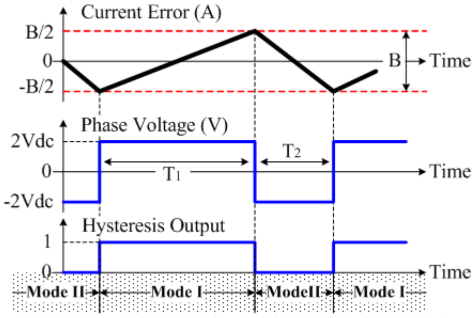


Fig. 4. Hysteresis operation with two-level modulation

For a voltage source inverter fed to a three-phase PMSM in the figure 1, any phase voltage of the motor windings is

$$V_x = R_s i_x + L_s \frac{di_x}{dt} + e_x + V_n \tag{1}$$

where x=a or b, R_s and L_s are the resistance and inductance of the motor, V_x, i_x and e_x are phase voltage, phase current and back-EMF of the motor windings.

During a short time duration of Δt, the equation (1) is rewritten as

$$\frac{\Delta i_x}{\Delta t} = \frac{1}{L_s}(V_{xn} - R_s i_x - e_x) \tag{2}$$

From equation (2) and figure 1, assuming of $V_{xn}=V_{dc}$ and $\Delta i_x=B$, the time durations of T_1 and T_2 are

$$T_1 = \frac{BL_s}{V_{dc} - R_s i_x - e_x} \tag{3}$$

$$T_2 = \frac{-BL_s}{-V_{dc} - R_s i_x - e_x} \tag{4}$$

The switching frequency for one complete switching transition is

$$f_s = \frac{1}{T_1 + T_2} = \frac{V_{dc}^2 - (R_s i_x + e_x)^2}{2BL_s V_{dc}} \tag{5}$$

Subsequently, when $R_s i_x + e_x = 0$, the maximum switching frequency occurs and is given as following:

$$f_s = \frac{V_{dc}}{2BL_s} \tag{6}$$

From (5), the hysteresis achieves constant frequency output if satisfying the following equation:

$$B = \frac{V_{dc}}{2L_s f_s}\left[1 - \left(\frac{R_s i_x + e_x}{V_{dc}}\right)^2\right] \tag{7}$$

To obtain accurate hysteresis band from the equation (7), for three-phase PMSM drives, variable band is directly calculated in the paper by the following conditions:

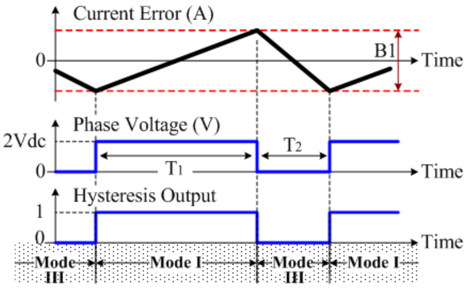
$$i_x = i_x^* \tag{8}$$

$$\begin{cases} e_a = \phi\omega\cos\theta \\ e_b = \phi\omega\cos(\theta - 2\pi/3) \end{cases} \tag{9}$$

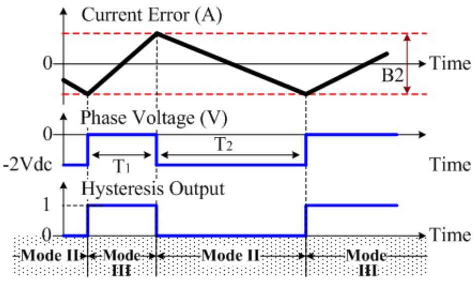
where '*' denotes the reference value, Φ is the flux linkage induced by the magnet, θ and ω are the position and speed of the rotor.

B. Proposed three-level hysteresis regulator with variable band

With three-level modulation the hysteresis operation contains two parts for positive and negative inverter outputs respectively with the shifted hysteresis bands of B1 and B2 shown in the figure 5 (a) and 5(b), and the operation parameters are given in the Table II and III. As shown in the figure 5, the current error is changed by the direction of the level of the inverter output voltage while the current error reaches the outer hysteresis boundary. In the process of positive inverter voltage output, the voltage level is positive when the current error reaches upper hysteresis boundary and zero when it reaches lower one. During negative inverter voltage output, the voltage level is negative when the current error reaches to upper hysteresis boundary and zero when it reaches to lower one. For zero level voltage output, the mode III and IV are used interchangeably and alternately.



(a) Positive inverter output



(b) Negative inverter output

Fig. 5. Hysteresis operation with three-level modulations for positive inverter output

1. Hysteresis operation during positive inverter output

As shown in the figure 5, with similar derivation in Part III.A, the time durations of T_1 and T_2 are

$$T_1 = \frac{B_1 L_s}{V_{dc} - R_s i_x - e_x} \tag{10}$$

$$T_2 = \frac{-B_1 L_s}{-R_s i_x - e_x} \tag{11}$$

The switching frequency for one complete switching transition is

$$f_s = \frac{1}{T_1 + T_2} = \frac{(V_{dc} - R_s i_x - e_x)(R_s i_x + e_x)}{B_1 L_s V_{dc}} \tag{12}$$

Subsequently, when $R_s i_x + e_x = V_{dc}$ the maximum switching frequency occurs and is given as:

$$f_s = \frac{V_{dc}}{B_1 L_s} \tag{13}$$

From (12), the hysteresis achieves constant frequency output if satisfying the following equation:

$$B_1 = \frac{V_{dc}}{L_s f_s}\left[\frac{R_s i_x + e_x}{V_{dc}} - \left(\frac{R_s i_x + e_x}{V_{dc}}\right)^2\right] \tag{14}$$

where i_x and e_x are calculated by the equations (8) and (9).

2. Hysteresis operation during positive inverter output

As shown in the figure 5, the times of T_1 and T_2 are

$$T_1 = \frac{B_2 L_s}{-R_s i_x - e_x} \tag{15}$$

$$T_2 = \frac{-B_2 L_s}{-V_{dc} - R_s i_x - e_x} \tag{16}$$

The switching frequency for one complete switching transition is

$$f_s = \frac{1}{T_1 + T_2} = -\frac{(V_{dc} + R_s i_x + e_x)(R_s i_x + e_x)}{B_2 L_s V_{dc}} \tag{17}$$

Subsequently, when $R_s i_x + e_x = -V_{dc}$ the maximum switching frequency occurs and is given as follows:

$$f_s = \frac{V_{dc}}{B_2 L_s} \tag{18}$$

From (17), the hysteresis achieves constant frequency output if satisfying the following equation:

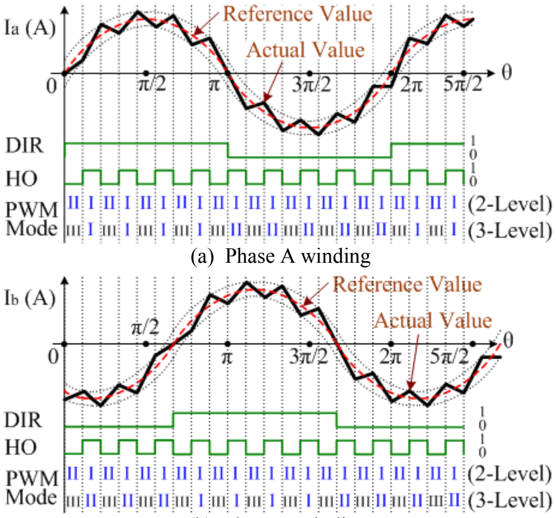
$$B_2 = \frac{V_{dc}}{L_s f_s}\left[-\frac{R_s i_x + e_x}{V_{dc}} - \left(\frac{R_s i_x + e_x}{V_{dc}}\right)^2\right] \tag{19}$$

where i_x and e_x is calculated by equations (8) and (9).

Using the equations of (14) and (19), the variable bands are calculated for the hysteresis controllers of three-phase PMSM drive. It is readily known from equations (6), (13) and (18) that the maximum switching frequency of the proposed three-level hysteresis controller is reduced to half compared to that of two-level version.

IV. IMPLEMENTATION OF PROPOSED SCHEME IN A THREE-PHASE PMSM DRIVE

A general PWM generation scheme of two-level and three-level modulation for three-phase PMSM drive with the hysteresis controller is illustrated in the figure 6, in which DIR is the polarity of the output inverter voltage, HO is the output value of the hysteresis, and two PWM modes are available for two-level and three level modulation. Two reference currents of i_a* and i_b* have 120 electrical degree phase shift with respect to each other. The digital realization of the proposed scheme is given in the table I. According to the currents between the reference and actual current and the direction of the output voltage of the inverter, the operating mode of the inverter is chosen to control the motor current varied in the given limitation. In the scheme, two modes of Mode I and II are used for two-level hysteresis modulation and four modes of Mode I, II and III are used for three-level hysteresis modulation. For three-level modulation, the polarity of the output inverter voltage is calculated by the rotor position where DIR=1 as the rotor position θ is in [2*k* π , (2*k*+1) π] and DIR=0 as θ ∈ [(2*k*-1) π , 2k π] for phase A current modulation, and DIR=1 as θ ∈ [(2k+1/2) π , (2k+3/2) π /2] and DIR=0 as θ ∈[(2k-1/2) π , (2k+1/2) π] for phase B current modulation.



(a) Phase A winding

(b) Phase B winding

Fig. 6. PWM scheme for three-level modulation

TABLE I
PWM SCHEME OF TWO- AND THREE- LEVEL HYSTERESIS MODULATION FOR THREE-PHASE PMSM DRIVES

Two-level modulation				Three-level modulation			
Band	DIR	HO	Mode	Band	DIR	HO	Mode
B	1	1	I	B_1	1	1	I
B	1	0	II	B_1	1	0	III
B	0	1	II	B_2	0	1	III
B	0	0	I	B_2	0	0	II

The overall configuration of the proposed three-level hysteresis control scheme is shown in Figure 7. In the diagram, the variable band of B1 and B2 can be calculated by the equations of (14) and (19). The principle of PWM and the polarity calculation of the output inverter voltage can be derived by the figure 6 and Table I.

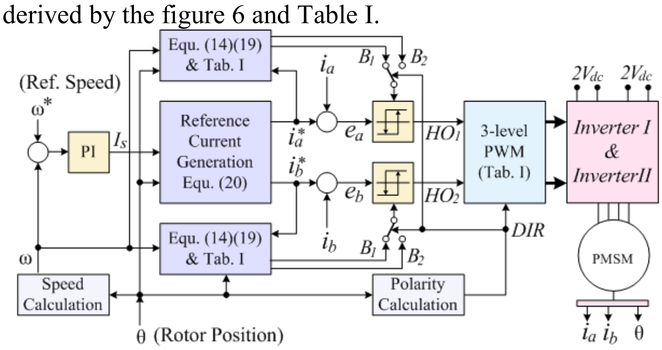


Fig. 7. The configuration of the proposed three-level hysteresis modulation for three-phase PMSM drives

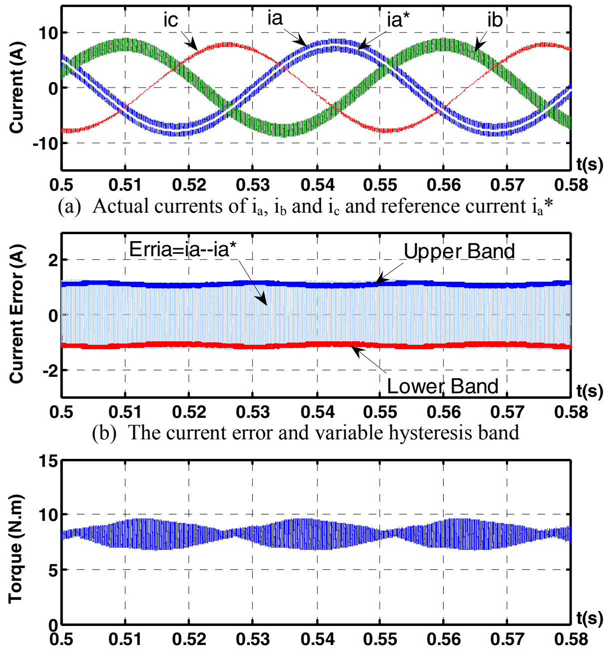
The reference current is calculated by the following:

$$\begin{cases} i_a^* = I_s \cos\theta \\ i_b^* = I_s \cos(\theta - 2\pi/3) \end{cases} \tag{20}$$

where the amplitude of reference current (I_s) is calculated by the speed PI controller.

V. Simulation Results

To verify the proposed scheme, a simulation model of MATLAB has been developed. A three-phase PMSM model was used in the simulation with the parameters of rated speed (3000rpm), armature resistance (2.87ohm), inductance (8.5mH), flux induced by the magnet (0.175Wb) and the pole pairs (4). In the simulated system, the DC-link voltage of the inverter was set to 155V. The reference speed of the motor was set to 300rpm and the load was 8Nm. The target average switching frequency is set to 3000Hz in the simulation of traditional and proposed hysteresis regulators.

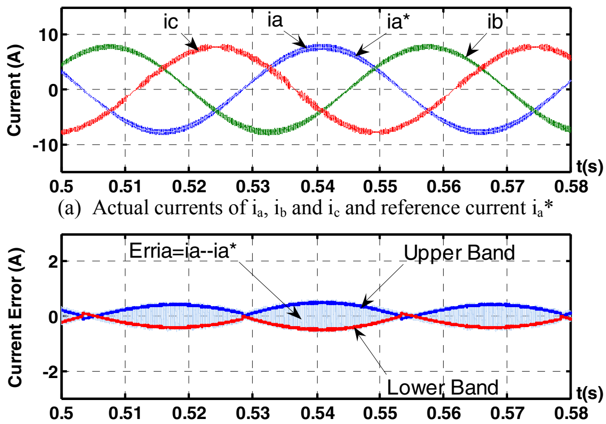


(a) Actual currents of i_a, i_b and i_c and reference current i_a*

(b) The current error and variable hysteresis band

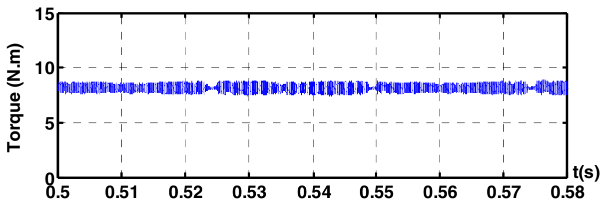
(c) The torque

Fig. 8. Two-level hysteresis controller with variable band for three-phase PMSM drives



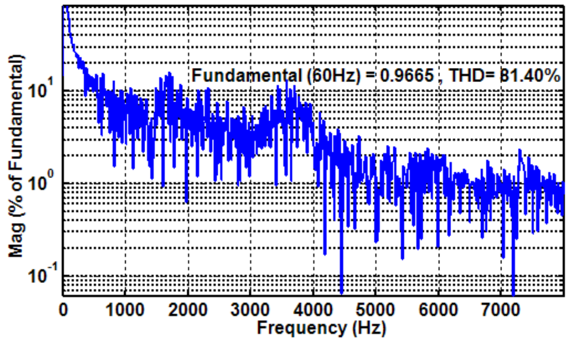
(a) Actual currents of i_a, i_b and i_c and reference current i_a*

(b) The current error and variable hysteresis band

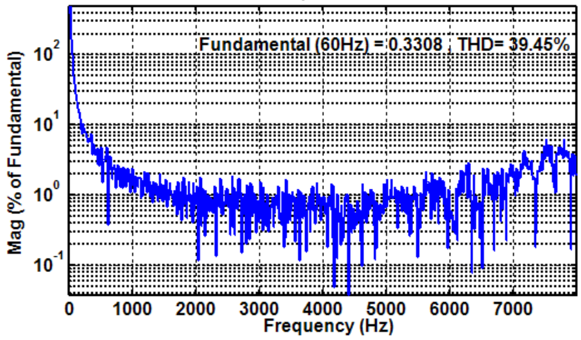


(c) The torque

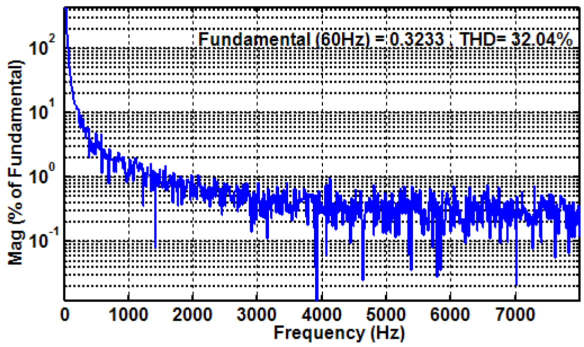
Fig. 9. Three-level hysteresis controller with variable band for three-phase PMSM drives



(a) Two-level hysteresis controller with constant band for six-switch inverter of figure 1



(b) Two-level hysteresis controller with variable band for eight-switch inverter of figure 2



(c) Three-level hysteresis controller with variable band for eight-switch inverter of figure 3

Fig. 10. Frequency spectrum of actual current (i_a) for three-phase PMSM drives as time = [0.5, 0.56]

Figures 8 and 9 are the responses of the measured and reference current, the current error and the torque in a three-phase PMSM drive fed by proposed inverter of figure 2 using two-level modulation and the proposed three-level modulation respectively. In the two-level hysteresis controller, the current error is controlled over a band of [-1.2A, 1.2A] and the torque varies in the band of [6.5N.m, 9.8N.m]. However, for three-level controller, the current error is in the band of [-0.6A, 0.6A] and the torque varies over [7.5N.m, 8.5N.m]. From the results under the same average switching frequency of 3030Hz, it is seen that the proposed three-level controller has better performance of lower current error and torque ripple compared with two-level strategy.

Figure 9 is the frequency spectrum responses of the phase current (I_a) during time = [0.5, 0.56] three-phase PMSM drives under the tests of three current regulators, which are two-level modulation with constant for six switch inverter of the figure 1, two- and three-level modulation with constant and variable band for the proposed inverter of figure 2 respectively. The total harmonic distortion (THD) of the three-level modulation method is clearly lower than two two-level value. Using the technique of variable band hysteresis, the improved hysteresis method also achieves lower harmonic distortion. Subsequently, from the simulation results of figure 8 and 9, it is known that the proposed current hysteresis controller having the functions of three-level modulation and variable band has higher control performance than the convention two levels approach.

VI. Conlusion

Improvement of the control performance of three-phase PMSM drives, based on traditional two-level hysteresis controller, a three-level hysteresis current controller with variable band is investigated in the paper. Though three switching modes of single-phase four-switch inverter, positive, negative and two zero voltage outputs are used to achieve the three-level modulation in the proposed three-phase PMSM drive. Also a variable hysteresis band method is proposed to obtain better harmonic performance of the proposed three-level hysteresis current regulator. The simulation results show the validity and effectiveness of the proposed three-level hysteresis current controller.

Acknowledgment

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