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An Adaptive Hysteresis Current Controller for Interior Permanent Magnet Synchronous Motor

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ABSTRACT: In this paper, adaptive hysteresis controller is proposed for the interior permanent magnet synchronous motor (IPMSM) to get more accurate, ripple less and better performance of IPMSM drive system than fixed band hysteresis current controller. Conventional current controller is popularly used because of simplicity, implementation and fast current control response. However there is a disadvantage, modulation frequency varies in a fixed band which results in non- optimum current ripple in the load. To overcome this, Bimal k. bose proposed adaptive hysteresis current control method where the band is modulated with the system parameters to maintain the modulation frequency to nearly constant. Park transformation is used to determine the d-q-0 reference frame for the suitable current reference signals. Comparative simulation results are demonstrated for IPMSM drive system with adaptive hysteresis current controller using MATLAB/Simulink

KEYWORDS: conventional current controller, current ripple, IPMSM, park transformation.

I. INTRODUCTION

From the last three decades AC machine drives are becoming more and more popular, especially Induction Motor Drives (IMD) and Permanent Magnet Synchronous Motor (PMSM), but with some special features, the PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor, and wide operating speed range like high performance applications, as a result, a gradual gain in the use of PMSM drives will surely be witness in the future market in low and mid power applications.

The behavior of Permanent magnet synchronous motor drive system predominantly depends on the characteristics of type of current control technique that we employ for the current control of Voltage Source Inverter (VSI). So, the current control of VSI is again another subject that we have to concern seriously for better performance of motion control drive applications. In this paper, the current controller has implemented in inner loop which generates the control gate signals for control of inverter output which in spite control output torque of IPMSM. Appropriate selection of controllable switches and current controller play an important role for the better efficacy of the VSI as well as drive system. The characteristics of various controllers that have been previously used as current controller for the speed control of IPMSM drive, it has been found that Adaptive Hysteresis Band Current Controller (AHBCC) can be used to achieve a better and satisfying control for the current controller [2-5]. Although fixed band hysteresis current controller is simple in implementation with less complexity but prior to it AHBCC has been preferred due to its some advantages over fixed band hysteresis current controller. So in this section, conventional fixed band hysteresis and adaptive hysteresis band current control technique has been discussed along with their design and implementation of adaptive hysteresis current controller in the drive system

II. MATHEMATICAL MODELLING OF IPMSM

A PMSM is composed of three phase's stator windings and permanent magnets mounted on the rotor surface (surface mounted PMSM) or buried inside the rotor (interior PMSM). The electrical equations of the PM synchronous motor can be described in the rotor rotating reference frame, written in the (*dq*) rotor flux reference frame [22].

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The mathematic model of PMSM is based on the following assumptions:
(1) Neglecting the armature saturation;
(2) Neglecting the of eddy and magnetic hysteresis losses;
(3) There is no rotor damp resistance.
(4) Induced EMF is sinusoidal
The relations of voltage, torque and flux of PMSM are described as follows:

$$\begin{bmatrix} \dot{i}_q \\ \dot{i}_d \end{bmatrix} = \begin{bmatrix} -\frac{L}{R} & -\omega_r \\ \omega_r & -\frac{L}{R} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & -\frac{\omega_r}{L} \end{bmatrix} \begin{bmatrix} u_q \\ u_d \\ \phi \end{bmatrix} \tag{1}$$

Where i_d and i_q are the *d* and *q* axis stator currents, *R* and *L* are the stator phase resistance and inductance respectively; ω_r is the rotor electrical speed;
u_d and u_q are the stator voltages expressed in the *dq* reference frame and φ is the flux established by rotor permanent magnets; *P* is the number of pole pairs. Equation (1) describes electrical dynamics and is nonlinear since they involve products of state variables.

$$\omega_s = P\omega_r \tag{2}$$

ω_r is inverter frequency
The electromagnetic torque is given by

$$T_e = 3P\left[\phi i_q + (L_d - L_q) i_d i_q\right] \tag{3}$$

If , $i_d = 0$ the electromagnetic torque *Te* is proportional to i_q .This description is similar to the torque generated in a DC motor with independent field excitation. This feature can simplify the controller design of the PMSM, which is used in the controller simulation experiment in this paper.
The equation of the motor dynamics is

$$T_e = T_L + B\omega_r + J\dot{\omega}_r \tag{4}$$

T stands for external load torque. *B* represents the damping coefficient and *J* is the moment of inertia of the rotor. Thus, the mechanical dynamic of the PMSM can be rewritten as

$$\frac{d\omega_r}{dt} = -\frac{B}{J}\omega + \frac{3P\left[\phi i_q + (L_d - L_q) i_d i_q\right]}{2J} - \frac{T_L}{J} \tag{5}$$

The equation (5) shows the electromagnetic torque is the product of state variables and it is nonlinear. The equations (1) and (5) constitute the whole control model of the PMSM.

The dq0 transform it is also known as park transformation. It is a space vector transformation of three phase time domain signals from a stationary phase coordinates (ABC) to a rotating coordinate system (dq0). The transform applied to time domain voltages in natural frame (i.e va, vb, vc) is as follows:

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r-120) & \cos(\theta_r+120) \\ \sin\theta_r & \sin(\theta_r-120) & \sin(\theta_r+120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Where $\theta = \omega t+\theta A$ is the angle between the rotating and fixed coordinate system at each time t and θA is an initial phase shift of the voltage.
The inverse transformation from dq0 frame to the natural abc frame:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r-120) & \sin\theta_r-120 & 1 \\ \cos(\theta_r+120) & \sin(\theta_r+120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix}$$

III. HYSTERIES CONTROLLER

Among various pulse width modulation techniques, conventional hysteresis band current controller is popularly used due to its simplicity in implementation. Hysteresis band current controller will try to keep the input current error within range of fixed band gap defined by upper and lower band. In this technique, the reference current of any phase is summed with the negative of the measured current value of that phase which will produce the current error, the current error is then provided to the input of the controller and it is compared with the defined fixed band and it gives the output as per the required characteristics gate driven signal as shown in fig1. The characteristics of hysteresis band is defined as "when the error crosses the lower limit of the hysteresis band, the upper switch of the inverter leg is switched ON, and when the error crosses the upper limit band, the bottom switch of the inverter leg is switched ON.
Let us assume current error is represented as δ
δ =reference current (I_{ref}) - actual current (I_{act}), then

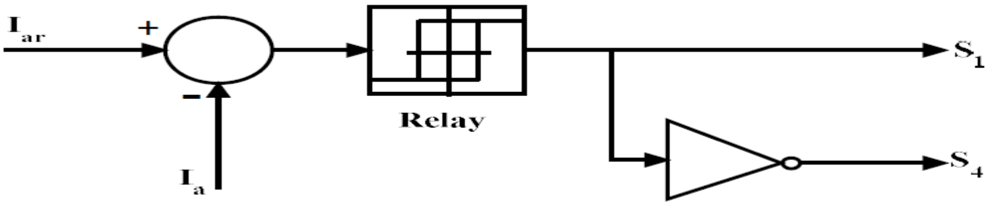

Fig.1 Schematic diagram of Hysteresis controller.

- If δ >HB upper switch of any single leg of VSI is ON (say Q1=1) and lower switch of same leg is OFF (say Q4=0).
- If δ <-HB upper switch of any single leg of VSI is OFF (say Q1=1) and lower switch of same leg is ON (say Q4=0).

For symmetrical operation of three phases, above logic is same but only band profile of other Phases will be displaced with 120°.The logic based upon which this controller generates the required gate drive signal can be easily understood from fig.2.

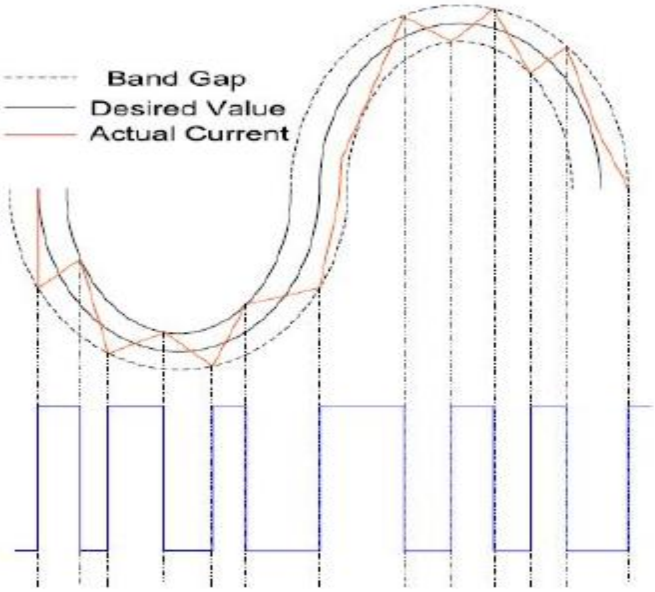

Fig.2 Hysteresis controller operation

Fixed band hysteresis band controller technique has various advantages such as simple implementation, good transient response, unconditioned stability and robust against parameter variation. But it has some drawbacks such as switching frequency is not constant i.e. variable switching frequency. Greater current ripple in steady- state, the modulation process generates undesired sub-harmonic components resulting in higher machine heating and no intercommunication between each hysteresis controller of other phases and hence no strategy to generate zero-voltage vectors, due to which the switching frequency increases at lower modulation index and the signal will leave the hysteresis band whenever the zero vector is turned on. To overcome the drawbacks novel method Adaptive hysteresis current controller is been implemented.

IV. ADAPTIVE HYSTERESIS CURRENT CONTROLLER MODELLING

The problem of fixed band hysteresis current controller can be alleviated by a novel adaptive hysteresis band current control technique where the band is a function of variation in load current, switching frequency (fs), counter emf (vf) and slope of reference current (m) [7]. Due to such controlled behavior of adaptive hysteresis band current controller we can get more accurate, ripple less and better performance of IPMSM drive system than fixed band hysteresis current controller.

Adaptive hysteresis band controller is modulated with system parameters to maintain modulation frequency constant. Although this strategy is applicable to general ac drives as well as other loads, an interior permanent magnet synchronous machine load is considered. Systematic analytical expressions of the hysteresis band have been derived as functions. IPMSM drive is been operated in isolated neutral with counter emf load is most practically used.
In this isolated neutral, the machine phase voltages interact with each other and no longer be 0.5vdc as like when neutral is connected as shown in fig.3.When Q1 is ON , the possible phase-a voltage may be 0, 1/3, 2/3Vdc, and when Q4 is ON, the corresponding voltage may be 0,-1/3, -2/3Vdc. Typical PWM phase voltage and current waves during a modulation cycle are shown in fig.3. With the assumed polarity of counter emf when Q1 is ON, the phase current in a time segment will rise or fall, respectively, depending on the dominating phase voltage or counter emf, but the current will always fall during the Q4-ON period.

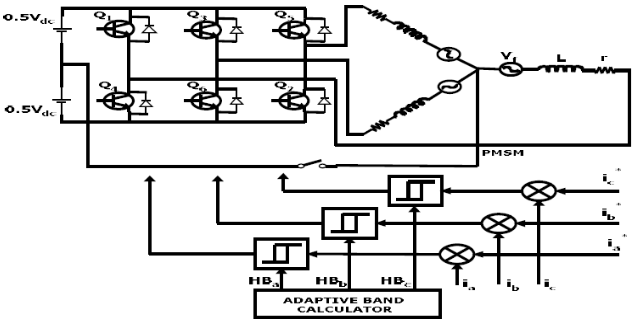

Fig.3: Adaptive Current controlled IPMSM drive system

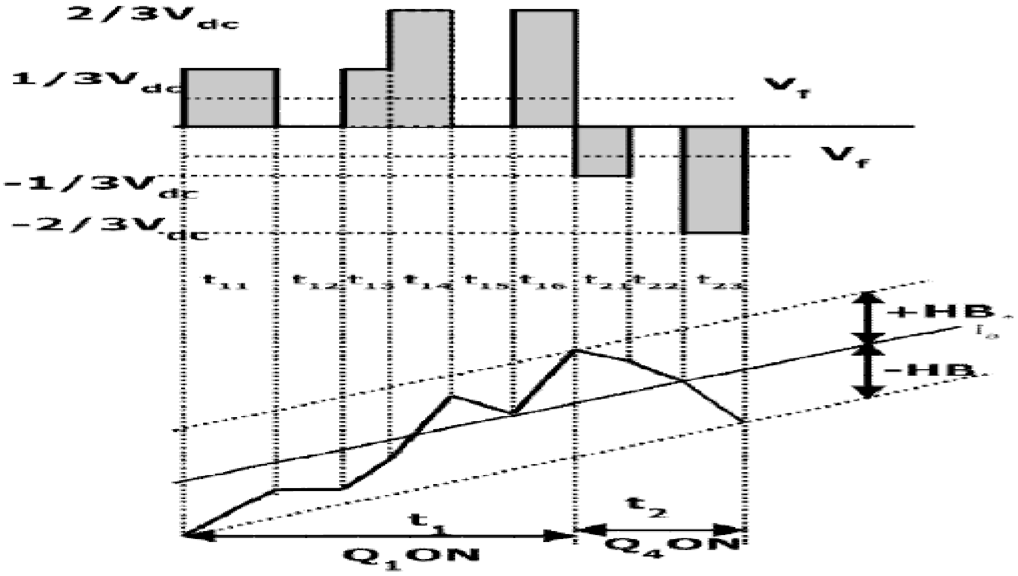

Fig.4: Typical PWM voltage and current waveform with Calculation of Hysteresis-band

This can be modelled and simulinked in MATLAB as shown in fig 5.

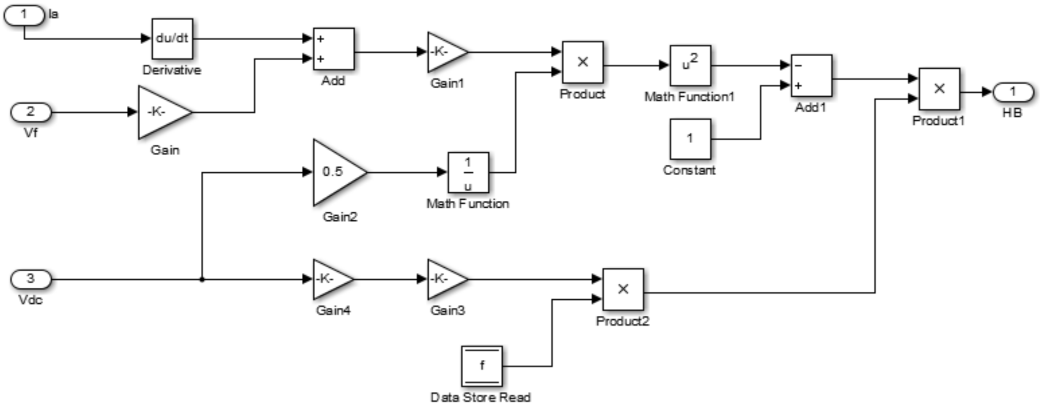

Fig 5. Adaptive hysteresis band calculation block diagram

V. RESULTS

The following MATLAB/Simulink results are for IPMSM drive system with fixed band current controller and adaptive hysteresis current controller. Comparing the results of both the controllers, we observe that the torque developed by the motor Te with AHBCC reaches steady state much faster than fixed band current controller as shown in fig.6 &7. The below figures also shows that three phase stator current and electromagnetic torque is very smooth with drastically reduction in ripples. Similarly speed response is smooth.

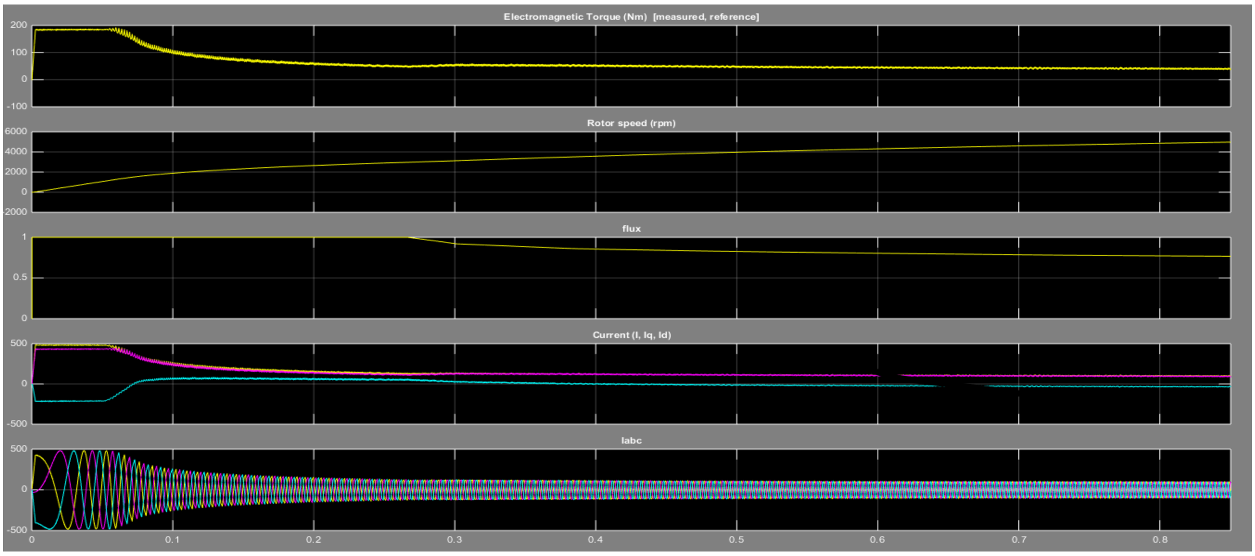

Fig.6 (a) electromagnetic torque (Te), (b) rotor speed, (c) current id,iq (d) stator current waveforms with Fixed band hysteresis controller.

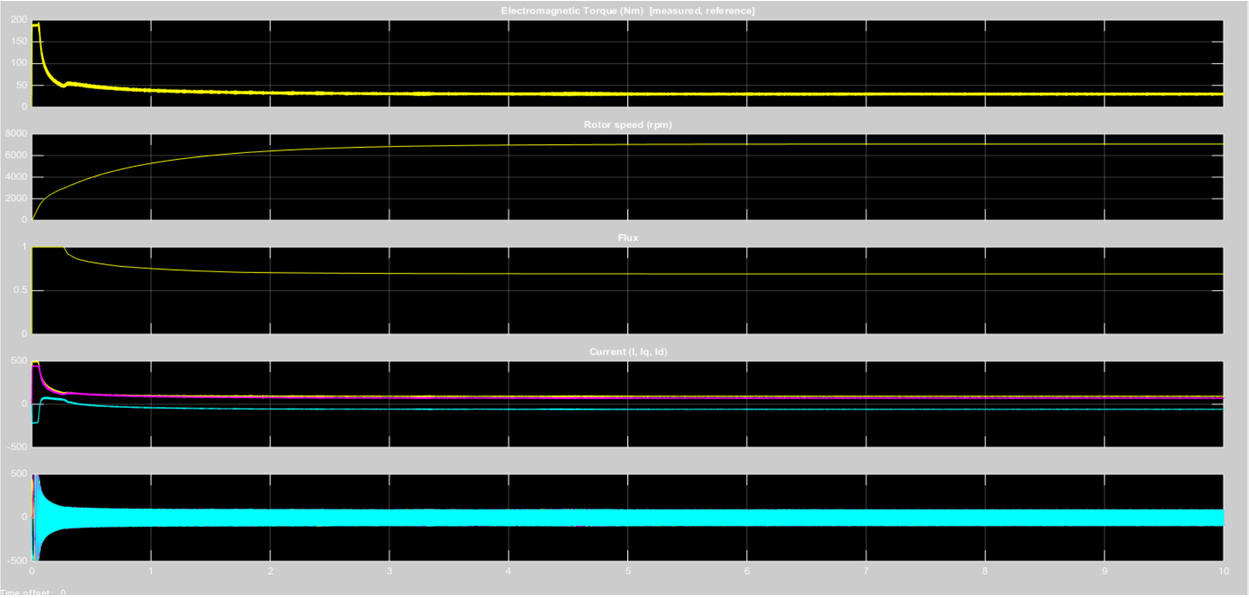

Fig.7 (a) electromagnetic torque (Te), (b) rotor speed, (c) current id,iq (d) stator current waveforms with Adaptive band hysteresis controller.

VI.CONCLUSION

Adaptive hysteresis-band current controller has been described in the paper. A hysteresis-band current controller is popularly used because it is simple to implement, has fast response, and peak current is automatically limited. The conventional fixed hysteresis-band current control generates excessive current ripple because modulation frequency varies within a band. In an adaptive hysteresis-band method, the band is modulated as a function of system parameters to maintain the modulation frequency to be nearly constant. An IPMSM drive system with the adaptive band has been simulated through MATLAB

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