Performance Study of Permanent-Magnet Synchronous Motor Drive by using Hysteresis Current Controller

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ABSTRACT
The permanent magnet synchronous motor (PMSM) drive has become competitive compared with other types of drive systems because of its simple and sensorless control algorithm. Modeling and simulation is usually used in designing PM drives compared to building system prototypes because of the cost.
This paper presents the Theoretical basis and some simulation and experimental results of hysteresis current controller for PMSM drive.

Keywords
PMSM; Hysteresis controller; modeling and simulation

1. INTRODUCTION
Basically, a current controller is usually preferred to follow the current command in some apparatus. These apparatus can be ac motor drives, active filters, UPS, and so on. Due to the application requirements and the advances of power electronics, current controller techniques have become an intensive research subject and various techniques for current controller have been proposed in recent years [1].

Hysteresis Current Control is an instantaneous feedback system which detects the current error and produces directly the drive commands for the switches when the error exceeds an assigned band. The advantages of this technique are high simplicity, good accuracy, outstanding robustness and a response speed limited only by switching speed and load time constant.

Predictive Current Control is a technique which predicts at the beginning of each modulation period the evolution of the current error vector on the basis of the actual error and of the load parameters and other load variables, the voltage vector to be generated by PWM during the next modulation cycle is thus determined so as to minimize the forecast error.
However, among these techniques, considering easy implementation, quick response, maximum current limit and insensitive to load parameter variations, the three-independent hysteresis current controller is a rather popular one. Nevertheless, due to lack of coordination among individual hysteresis controllers of three phases, very high switching frequency at lower modulation index may happen. This will of course increase the switching loss. In addition, the current error is not strictly limited. Double current error magnitude permitted by one hysteresis controller may occur. Recently Kazmierkowski et al. [2] have proposed a three-level hysteresis strategy to coordinate the switches of three phases in the d-q plane and apply zero voltage vectors for reducing the switching frequency. By transforming into the d-q domain, coordination of the three phase switching can be considered. Only two hysteresis controllers are required for three phases. In addition, zero voltage vector can be applied while encountering the zero current error to reduce the switching frequency. However, up to now, there is not any hysteresis controller which has used the information of the derivative of the current error. Since the command signal and the load terminal voltage source may greatly influence the current error control under some conditions, if some information of the derivative of the current error is also available, then one would know the changing tendency of the current error. Therefore, one can take more advantages of the zero voltage vector to reduce the switching frequency greatly. In this paper, an improvement of the conventional hysteresis current controller is proposed.

The paper is organized as follows: Section 2 presents the mathematical model of the PMSM. Predictive controller is described in section 3.PWM current controller is explained in Section 4. The operation of the Hysteresis current controller is discussed in Sections 5 & Flowchart in section 6 while the structure of the entire drive system is explained in Section 7. Sections 8 and 9 have the results and conclusion, respectively.

2. MATHEMATICAL MODEL
The stator of the PMSM and the wound rotor SM are similar. The permanent magnets used in the PMSM are of a modern rare-earth variety with high resistivity, so induced currents in the rotor are negligible. In addition, there is no difference between the back EMF produced by a permanent magnet and that produced by an excited coil. Hence the mathematical model of a PMSM is similar to that of the wound rotor SM.

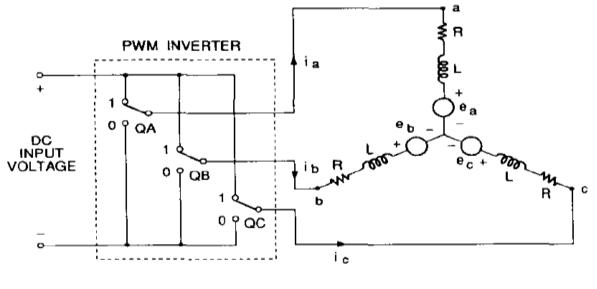


Fig 1 Equivalent circuit of drive

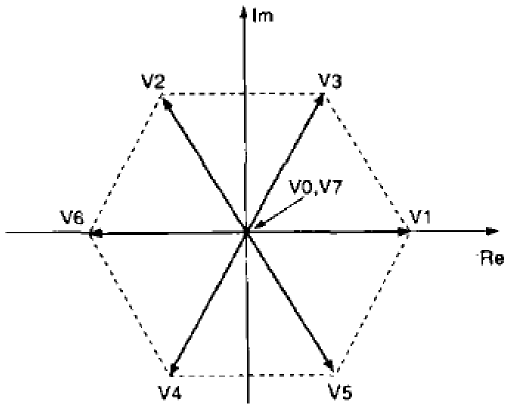


Fig 2 Inverter voltage space vectors.

The following assumptions are made in the derivation.

1) Saturation is neglected although it can be taken into account by parameter changes.

2) The induced EMF is sinusoidal.

3) Eddy currents and hysteresis losses are negligible.

4) There are no field current dynamics.

5) There is no cage on the rotor.

With these assumptions, the stator d, q equations of the PMSM in the rotor reference frame are as follows:

$U_q = Ri_q + P\lambda_q + \omega_s\lambda_d$ (1)

$U_d = Ri_d + P\lambda_d - \omega_s\lambda q_d$ (2)

Where

$\lambda_q = L_q\, i_q$

And

$\lambda d_q = L_d + \lambda_{af}$

Ud and Uq are the d, q axis voltages, i_d and i_q are the d, q axis stator currents, L_d and L_q are the , d q axis inductances, λ_d and λ_q are the , d q axis stator flux linkages, while R and w_s are the stator resistance and inverter frequency, respectively. λ_{af} is the flux linkage due to the rotor magnets linking the stator.

3. PREDICTIVE CURRENT CONTROLLER

In this scheme, the motor current vector is controlled by an unique controller instead of three independent controllers as in hysteresis control scheme. The currents are sampled at a constant rate. The current vector is calculated and compared to the reference current vector. An appropriate voltage vector that would reduce the current error vector Δ i to zero is calculated. This calculation can be based on the simplified motor equivalent circuit shown in Fig.1.The required voltage vector at the k-th sampling instant is given by

V(k)= e (k) + L di(k)/dt + Ri(k) (3)

Where V is the inverter voltage space vector, e is the emf space vector, i is the motor current space vector, L is the stator inductance (per phase), R is the stator resistance (per phase).

In permanent-magnet synchronous motors, the armature reaction is usually negligible so that the emf space vector necessary for the solution of (3) can be determined with acceptable accuracy from the speed and position information. If the emf is sinusoidal, it can be calculated as

e = Em, sin (nθ) (4)

Where E, is the emf amplitude, n is the number of pole pairs, and θ is the rotor position. The emf amplitude is a function of the motor speed. It can be approximated as

$Em = Em\,(nom)\,[\,\omega / \omega_{nom}]$ (5)

Where E, (nom) is the emf nominal amplitude, ω is the motor speed, and ω_{nom} is the nominal speed. The position θ is obtained from the position sensor that can be an absolute or incremental optical encoder or a resolver. In this case where the emf is of arbitrary form, it can be calculated as

ea = E m * f (θ) (6)

Where E_m, is the emf amplitude given by (5) and f (θ) is the form function pf stored in a look-up table. The difference equation is

V (k) = e (k) + (L/T) [i*(k + 1) - i (k)] + Ri(k) (7)

where V(k) is the inverter voltage vector, e(k) is the emf vector, i(k) is the actual current vector at k^{th} sampling instant, i* (k + 1) is the reference current vector at $(k + 1)^{th}$ sampling instant, T is the sampling period.

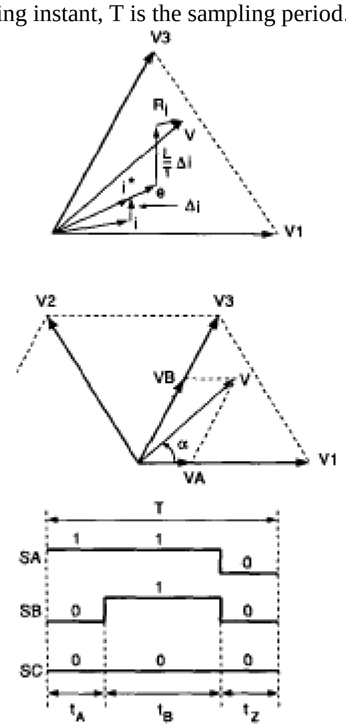


Fig 3 Predictive current control scheme

The predictive current control principle is illustrated by the vector diagram shown in Fig. 3. The required voltage vector to force the current vector to follow the current reference vector is obtained by additional three vectors

E (k), (L/T) Δi(k) , and Ri (k)

Pulse width modulation can be used to provide the voltage vector V. The inverter is switched from V1 to V3 with the duty cycle determined by the value of V1, and V3. By referring to Fig. 3, the voltages VA and VB can be determined as,

$VB, = \sqrt{2/3}\, V \sin \alpha$ (8)

$VA = V \cos\alpha - 0.5\, VB$ (9)

The time durations of the states 1 and 3 and the zero voltage state are given by

$t_A = 1.5(VA/V_{dc})T$ (10)

$t_B, = 1.5(VB/V_{dc})T$ (11)

$t_z = T - t_A - t_B$ (12)

where T is the sampling period and V_{dc} is the dc input voltage. With the condition $T= t_A + t_B + t_z$, It can be shown that the obtainable voltage vector resides inside the hexagon formed by the six active voltage vectors corresponding to six active states of the inverter.

4. PWM CURRENT CONTROLLER

A method used to generate the require currents is to use a pulse width modulated (PWM) stator current controller. The actual values of the three stator currents are measured and compared to the reference currents. Thus error currents are generated. These error currents are compared to a sawtooth-shaped triangular wave. If the current error signal is positive and larger than the sawtooth, the voltage is switched positively, while if the current error signal is positive and smaller than the sawtooth, the voltage is switched negatively. Note that it is unnecessary to use complementary switching to achieve this voltage profile.

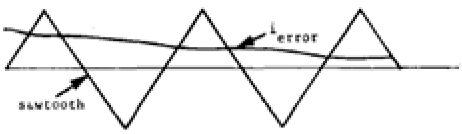


Fig 4 Triangular reference current.

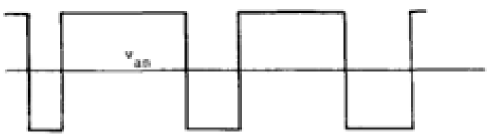


Fig 5 Pulse width-modulated current controller.

For example, if T1 is conducting, Van is equal to Udc / 2, where Udc/2 is the dc supply voltage and the reference is taken as the midpoint of the supply. By switching T1 off, the freewheeling diode across T4 immediately starts conducting to maintain the current flow through the motor inductance. This automatically forces Van to equal to Udc/2 even though T4 is not yet conducting. This is called a PWM current controller because of the pulse width modulation of the voltage

The advantage of the PWM current controller over hysteresis is that the switching frequency is preset, and it is, therefore, easy to ensure that the inverter switching capability is not exceeded. In the hysteresis controller the switching frequency depends on the value of the hysteresis window, and the actual switching frequency demanded from the inverter is unknown. A trial-and-error procedure must be adopted to ensure that the inverter switching frequency is not exceeded.

The advantage of the hysteresis controller over the PWM controller is that, from a control point of view, there is no transportation delay or system lag. In the PWM controller this does exist with the average lag being equal to half the period of the PWM.

5. HYSTERESIS CURRENT CONTROLLER

The operation of the hysteresis current control is explained by circuit shown in figure.6 The purpose of the current controller is to control the load current by forcing it to follow a reference one. The load currents are sensed and compared with the respective reference currents, the error signal passes through three independent hysteresis comparators having hysteresis band H. The output error currents of comparator are used to active the inverter power switches. Based on band, there are two types of current controllers, namely, fixed band hysteresis current controller and sinusoidal band hysteresis current controller. Here we are concentrating on fixed band current controller.

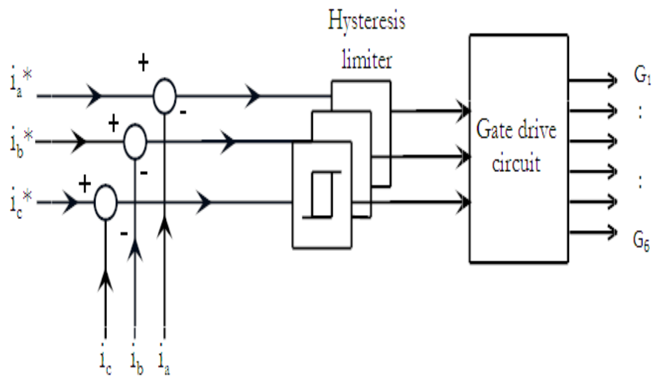


Fig 6 Basic circuit diagram of hysteresis controller

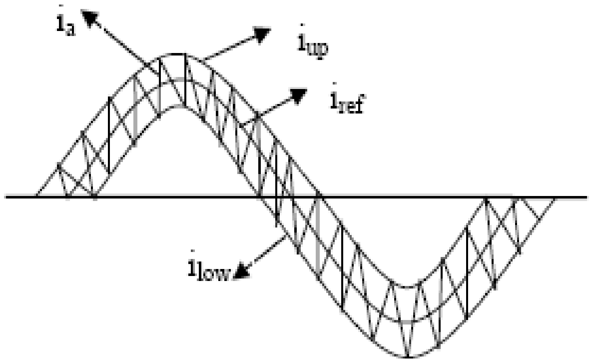


Fig 7 Hysteresis controller control structure

The waveform of fixed band hysteresis current controller is shown in figure 7. In the fixed band scheme, the hysteresis band is fixed over the fundamental period. The mathematical equations for fixed band control are given as follows:

$I_{ref} = I_{max}$ Sin wt (13)

$I_{up} = I_{ref} + H$ (14)

$I_{lo} = I_{ref} - H$ (15)

Where i_{up} is the upper band, i_{lo} is the lower band, and H is the hysteresis band limit. From figure 7, if ia >iup, then NA=0, which means that inverter output is negative in order to reduce line current. Similarly if ia< i_{lo}, then NA=1, where the inverter voltage is positive, in order to increase the load current. The same sequence is followed to other to sequences.

The advantage of this controller lies in its simplicity and its providing of excellent dynamic performance. Thus, it has most extensively used. On the other hand, the disadvantage is that the switching frequency varies during fundamental period, resulting in irregular operation of the inverter. As a result the switching losses are increased.

The power circuit that drives the PMSM is shown in Fig.8

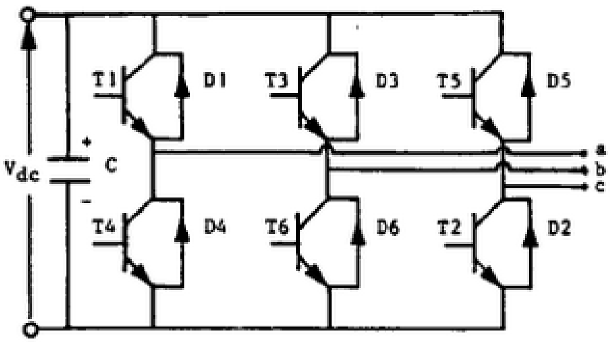


Fig 8 power circuit that drives the PMSM

It is assumed that a reasonably well-filtered dc supply is available. The six switches T1-T6 are used to control the three stator phase currents. The control strategy is as follows.

The actual values of ia and ib that are flowing into the motor are measured. From this ic can be constructed; this removes the need for an additional current sensor. The actual and reference values are compared and error signals generated. In making the comparison between the actual currents and the reference values, in addition, two other curves consisting of ia*+Δi and ia*- Δi are shown. Δi defines the hysteresis bands. The hysteresis property allows the actual value of ia to exceed or be less than the reference value by Δi. The logic is shown in Table 1.

Similar logic are applies to the other two phases.

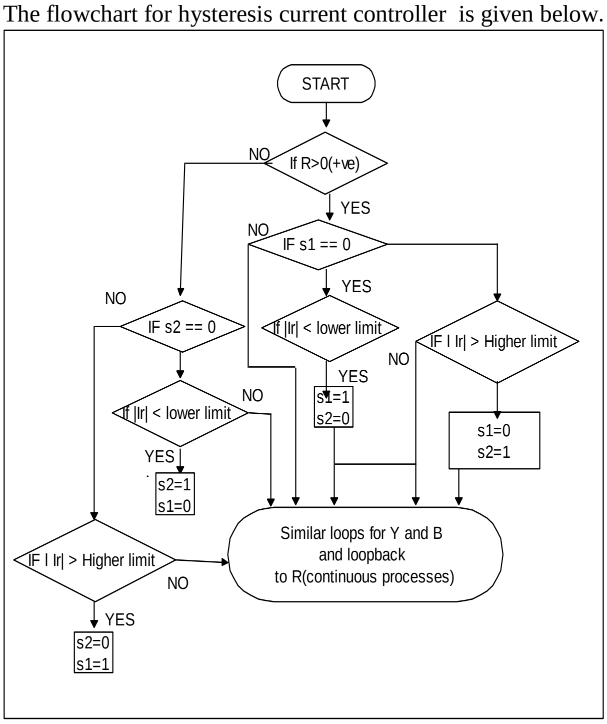
Table 1

i	*ia*	T1	T4
≥ 0	ia ≤ ia* - Δi	ON	OFF
≥ 0	ia ≥ ia* + Δi	OFF	OFF
< 0	ia ≥ ia* + Δi	OFF	ON
< 0	ia ≤ ia* - Δi	OFF	OFF

Whenever T1 is "on," i_a increases positively using either the B or C phases as a return path. As soon as T1 switches from an "on" to an "off" position, and since the current through the machine winding cannot go to zero instantaneously, the freewheeling diode across its complementary transistor, in this case T4 begins to conduct the phase a current. When this occurs, the voltage of phase A switches from +Udc/ 2 to -U dc / 2, where the midpoint of the do supply Vdc is taken as the reference. The opposite occurs when T4 switches from "on" to "off." A similar procedure exists in the other phases. The reason that this is called a hysteresis controller is that the phase voltage switches to keep the phase currents within the hysteresis bands. The phase currents are, therefore, approximately sinusoidal: the smaller the hysteresis bands, the more closely do the phase currents represent sine waves. Small hysteresis bands, however, imply a high switching frequency, which is a practical limitation on the power device switching capability. Increased switching also implies increased inverter losses.

6. FLOWCHART

The flowchart for hysteresis current controller is given below.



7. DRIVE SYSTEM

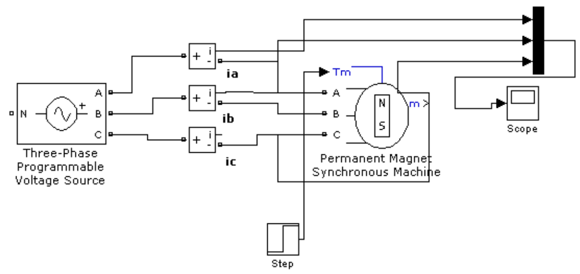


Fig 9 Model of PMSM drive for Measurement of current

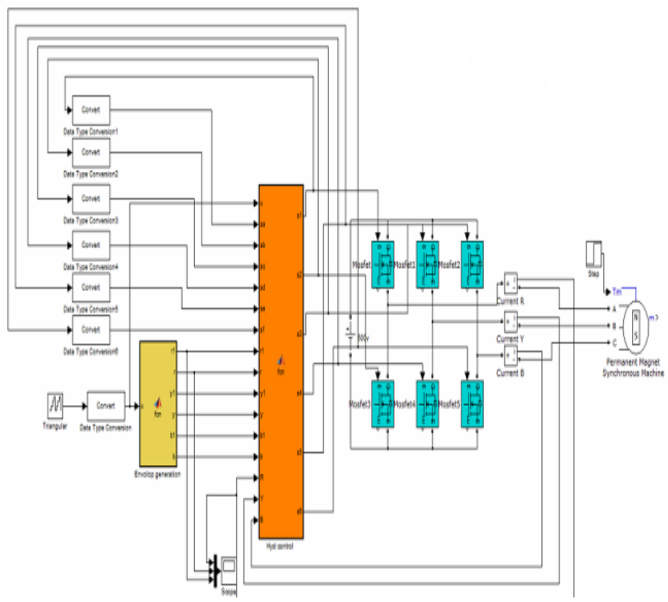


Fig 10 Matlab/Simulink Model of PMSM drive

Machine constitutes the PMSM drive system with current controller with embedded block and inverter as shown in Figure 10. The error between the reference and actual current is operated by the hysteresis controller. If input R is greater than r then switch S1is off and S2 is on. If R is less than R1 then S1 is on and S2 is off. The same can be applicable for other two phases.

8. RESULT

This paper has presented the modeling, simulation, and Analysis of PMSM drives by using hysteresis current controller. Initially hysteresis envelop is generated by using embedded function. The matlab simulation for PMSM drive system is shown in Fig 11 .The load currents are sensed and compared with the respective reference currents, the error signal passes through three independent hysteresis comparators having hysteresis band H. In this simulation hysteresis band is fixed over the fundamental period.

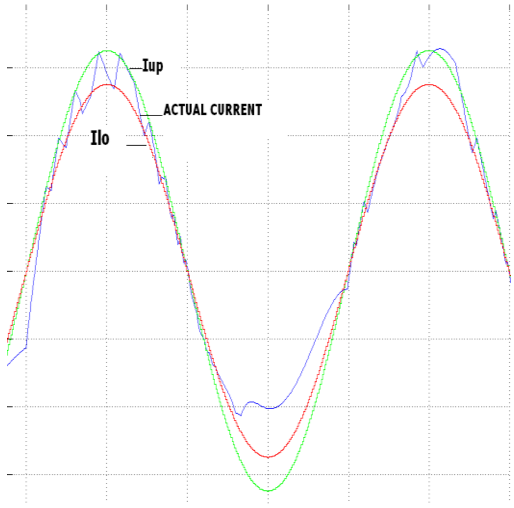


Fig 11 Simulation of Hysteresis Current Controller for PMSM drive

9. CONCLUSIONS

In this paper, the performance of current control PMSM drive system has been studied by employing hysteresis current controller. Hysteresis current controller largely reduces the torque ripple in turn, it can provide smooth running of PMSM drive system during low speed operation. Hysteresis current controller can enable to track the load current with reference current at a faster rate in order to improve the dynamic response of the system and it takes less computation time. Hysteresis control, in their improved version, are well suited to fast, accurate conversion systems. Interesting perspectives seem to come also from various controls, such as neural networks and fuzzy logic.

SPECIFICATIONS OF MOTOR:

SR.No	Motor Specifications	Value
1	Rated Torque	2.8 Nm
2	Rated Speed	4250 RPM
3	Resistance	1.6 Ω
4	Inductance	0.006365H
5	Magnet Flux	0.1852 Vs
6	DC link Voltage	300V

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