Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

A Vector Control Method of PMSM Using Single Phase Current Sensor

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Abstract - **This paper presents a new method of realizing vector control for the surface mounted permanent magnet synchronous machine (PMSM) using single phase current sensor. A simplified estimating method of phase current, which only requires the information from single phase current sensor and motor position sensor, has been proposed in this paper. Compared with the classical approaches, based on the reference current in synchronous rotor frame, the proposed method can get better accuracy, especially when there is a sudden change of the reference current. Furthermore, the method not relays on the model and parameters of PMSM and the control performance of current close-loop and also not sensitive to working conditions. The extensively experimental results under different work conditions, based on MATLAB/SIMULINK, have validated the feasibility and robustness of the proposed vector control method.**

Index Terms –Permanent magnet synchronous machine (PMSM), current sensor, current estimation, vector control, amplitude tracing.

I. INTRODUCTION

DUE to higher power density and efficiency, permanent-magnet synchronous machines (PMSM) have received increasing attentions in the last decades [1]. As realizing the decoupling of flux and torque, field-oriented control (FOC) or vector control method offers high performance of PMSM and has become an general industry standard [2]. Consequently, the current measuring plays an important role in pulse-width modulation voltage source inverters for PMSM. Usually, two or three phase currents are sampled based on current sensors installed on motor windings. In order to reduce cost and size, efforts have been put to complete FOC using single current sensor. It is very meaningful in the scene of limited volume, such as the joint drive of space manipulator.

At present, several useful control methods based on single current sensor have been developed by researchers. Almost of these methods are based on reconstructing phase currents from the current signal of dc-link. However, because the active vectors in a PWM period are present only for a very short time, there are practical difficulties to extract accurate phase currents from the current sensor on dc-link. Therefore, different method has been proposed to ensure a minimum amount of time for the active vectors. The methods can be divided into three categories [3]: 1) PWM modification method [4,5]; 2) the state observer algorithms [6,7,8]; 3) measurement vector insertion approaches [9,10]. However, the additional computational burden will be introduced into the controller inevitably. Different from the current reconstructing technologies from dc-link current information, in [11] a topology for matrix converter using only one current sensor is proposed, where the phase currents can be measured using single Hall current sensor that located on two of the three windings of motor. In [12], an estimating method is proposed for phase current form the reference current in the synchronous rotor frame. However, this method relays on the performance of close-loop controller for the currents of d-phase and q-phase in the synchronous rotor frame. Furthermore, estimated error will be very large when the value of q-phase current (i_{qref}) changes a lot suddenly.

This paper will introduce a new simple estimating method for phase current, which based on tracing the amplitude of measured current of another phase. The organization of this paper is as follows: the driver system of PMSM and reference frames for vector control will be introduced in section II. In section III, the basic principle and limitation of current estimation method based on reference current will be analyzed first. Then the proposed estimating method based on amplitude tracing will be given in detail. In section IV, extensively experimental result under different work conditions will be discussed, including reference current disturbance, step response of speed, ramp response of speed and load disturbance。

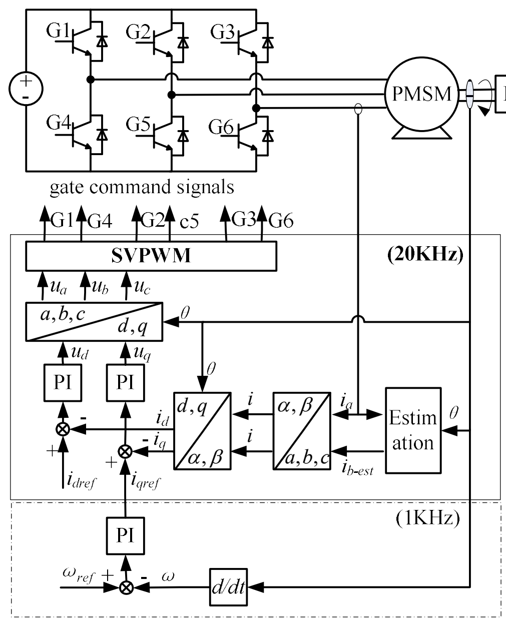

Fig. 1 Block diagram of the PMSM drive

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II. SYSTEM DESCRIPTION

The PMSM drive adopted here consists of a DC voltage source, a three-phase inverter, a PMSM motor, and a workload, as given in Fig.1. One current sensor, which based on close-loop-Hall-effect, has been used to measure one of the three phase currents of the motor windings, taking a-phase as example. A rotor position sensor has also been integrated on the rotor of motor. The field oriented control (FOC) method, which based on the space vector pulse width modulation (SVPWM) control mode, is used to provide three-phase balanced sinusoidal current to PMSM. Under normal working conditions, the phase currents of stators (i_a, i_b, i_c) can be expressed by

$$\begin{cases} i_a = i_m \sin(\omega t+\varphi) \\ i_b = i_m \sin(\omega t - 2\pi/3+\varphi) \\ i_c = i_m \sin(\omega t - 4\pi/3+\varphi) \end{cases} \quad (1)$$

where i_m is the current amplitude, ω is the electric angular frequency, φ is the initial phase angle (in this paper φ=0).

Fig.2 gives the coordinate system related in FOC. The a-phase (of three-phase stationary-frame: *A-B-C*) is alonging the same axis of the α-phase (of the two-phase stationary-frame: *α-β*). The angle between the d-phase(of the two-phase synchronous-frame: *d-q*) and the α-phase is defined as θ ($\theta=\omega t$). Clarke and Park transition matrix are used to transform the three-phase stator current, *i.e.* i_a, i_b, i_c, to the torque feedback current i_q and the field flux feedback current i_d, respectively. Two PI controllers are used to adjust the i_q and i_d to track their reference values (i_{qref} and i_{dref}), and export the desired voltage commands, *i.e.* u_q and u_d, which are transformed back to the *α-β* frame for controlling the SVPWM module. As to nonsalient pole PMSMs, the reference current i_{dref} is usually set to zero for minimizing the losses and the motor torque. In addition, another PI controller is used to complete speed control.

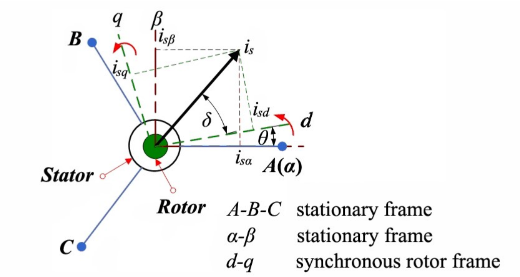

Fig. 2 Reference frames for vector control.

III CURRENT ESTIMATE METHODS

The α-phase and β-phase currents are calculated using the transformation matrix given by (2). A close inspection of (2) reveals that the current i_a has relationship with both of i_α and i_β. While, i_b just has relationship with i_β. When only one current sensor, the measurement of phase current should be defined as i_a and the α-phase are along the same axis of a-phase. Furthermore, the estimation value of i_b or i_β is used to implement vector control.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = K \begin{bmatrix} 3/2 & 0 \\ \sqrt{3}/2 & \sqrt{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (2)$$

where, '*K*' is a constant. The value of K is set to be 1 with the available literature [13].

In this section, the estimating method (of i_{β_est} or i_{b_es}) based on the reference current in synchronous rotor frame will be discussed first. Then, an improved estimating method is proposed, based on tracing the amplitude of measured current.

A. Estimating method based on reference currents

Assuming that the two PI controller can adjust the i_{sq} and i_{sd} to track their reference values of d- axis currents and q-axis currents (i.e. i_{dref} and i_{qref}) very well. The currents of α-phase and β-phase also can be estimated in the two-phase stationary reference frame using (3)[12].

$$\begin{bmatrix} i_{\alpha\_est} \\ i_{\beta\_est} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_{dref} \\ i_{qref} \end{bmatrix} \quad (3)$$

As the current i_{dref} usually sets to zero, the estimation value of i_{β_est} can write as:

$$i_{\beta\_est} = \cos(\theta) i_{qref} \quad (4)$$

Using i_{β_est} to replace i_β, the feedback current in d-q frame can be express as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_{\beta\_est} \end{bmatrix} \quad (5)$$

Put(4) and (5) together, we can get:

$$i_d = \cos(\theta) i_\alpha + \sin(\theta)\cos(\theta) i_{qref} \quad (6)$$

$$i_q = -\sin(\theta) i_\alpha + \cos(\theta)^2 i_{qref} \quad (7)$$

Using two PI controllers of current loop, i_d=0 and i_q=i_{qref} can be realized. Therefore, (8) can get either for (6) or (7):

$$i_a = -\frac{2}{3} i_{qref} \sin(\theta) \quad (8)$$

This means that both PI controllers in FOC are used to ensure the relationship between i_α and i_{qref}. Furthermore, basing on (2), (4) and (8), the estimation of i_{b_est} can be expressed as

$$i_{b\_est} = -\frac{2}{3} i_{qref} \sin(\theta - \frac{2\pi}{3}) \quad (9)$$

There, the reference current value of i_{qref} is directly used as the feedback value of b-phase (i_{b_est}), without taking care of the amplitude of a-phase value. However, when there is a sudden change of i_{qref}, the error of estimation cannot be neglected. In addition, if the performance of PI controllers is not good enough, estimating error will also increase.

B. Estimating method based on amplitude tracing

To overcoming the shortcoming of above estimating method for phase current, this paper has proposed a new simple estimation method of phase current, based on tracing the amplitude of the measurement value from the current sensor on a-phase. The basic principle will be introduced here.

From (1) we can know that the current in the three phases of PMSM is balanced, which means the amplitude of i_a and i_b are equal to each other. Thus, if we know the amplitude of i_a

(or i_m), the current in b-phase can be got according to (1). Therefore, the question of estimating i_b is changing to the estimation of i_m using the measured current i_a, rotor angle θ, and the sinusoidal current model in (1).

Obviously, the amplitude can be calculated from $i_a/\sin(\omega t)$. However, when $\sin(\omega t)$ equals to zero, it is not suitable for division operation. Assume that the estimation of current amplitude is i_{m_est}, the estimation of a-phase current can be expressed with (10). The error between the estimated value and the measured value can be expressed using (11). Therefore, if we can eliminate the error Δi_a in real time, the amplitude of current can be got accurately.

$$i_{a\_est} = i_{m\_est} \sin(\omega t) \tag{10}$$

$$\Delta i_a = i_m \sin(\omega t) - i_{m\_est} \sin(\omega t) = (i_m - i_{m\_est}) \sin(\omega t) \tag{11}$$

PI controller has the advantages of simple principle, easy to implement, independent control parameters and simple parameter selection. It is still the most widely used closed-loop controller at present. The speed loop and current loop of motor drive are using PI controllers. Although there is sinusoidal function in (11), the sinusoidal function can be considered as a gain factor of the controller, changing with the angle of rotor. Thus, PI control is very suitable to deal with this problem of trajectory tracking. The estimation scheme is given in Fig.3. The reference of PI controller is the absolute value of i_a, and feedback value is the absolute value of i_{a_est}, while the output is the estimation of amplitude (i_{m_est}).

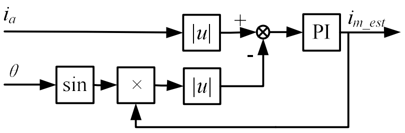

Fig.3 Diagram of estimating the amplitude of a-phase current

When we get the estimation value of i_{m_est}, the current of b-phase current can be got using (12). However, the tracking error will act on the estimation value directly. Aiming to decrease the negative influence of tacking error, the expression of i_{b_est} can be rewrite as (13), based on trigonometric function knowledge. Thus, the estimating value of i_{b_est} can be get with good accuracy. Furthermore, the method not relays on the model and parameters of PMSM, not on the control performance of current close-loop and not sensitive to working conditions, such as workload.

$$i_{b\_est} = i_{m\_est} \sin(\omega t - 2\pi/3) \tag{12}$$

$$\begin{aligned} i_{b\_est} &= i_{m\_est}(\sin(\omega t)\sin(-2\pi/3) + \cos(\omega t)\cos(-2\pi/3)) \\ &= -\frac{1}{2} i_a + \frac{\sqrt{3}}{2} i_{m\_est} \cos(\omega t) \end{aligned} \tag{13}$$

IV. Simulation Results

The proposed vector control method of PMSM drive based on single current sensor is simulated in MATLAB/Simulink software environment. The parameters of PMSM used in following simulation are given in Table 1. During the simulation, discrete solver with fix-step (5e-5s) has been used. Firstly, the simulation results of current controller under a disturbance will be presented, which shows the robustness of current estimator. Thereafter, the simulation results under other operating conditions are presented.

Table 1 Parameters of the PMSM in simulation

Parameters	value
EMF waveform	Sinusoidal
Stator phase resistance (ohm)	1.6
Ld(H) Lq (H)	[0.006365 0.006365]
Flux Linkage (V.s)	0.1852
Voltage Constant (V/krmp)	134.3663
Torque Constant (N.m)	1.1112
Inertia (kg.m^2)	0.0001854
Friction (M.m.s)	5.396e-5
Polepairs	4

A. Performance of the Current Estimator

The performance of the driving system under a disturbance in i_{qref} is present here first, to compare the ability of anti-disturbance of the two current estimators. Fig.4 shows the experiment situation considered here. The drive is working under steady state at the speed of 105 rad/s, and with corresponding reference current on q-axis (i.e., i_{qref}) of 0.25 A. At 1.5 s, a disturbance (Δi_{qref}) in the form of a step command is added to i_{qref} (i.e., Δi_{qref} =0.18 A). Thus, the system is subjected to a error with the amplitude about 72% of the original reference currents in q-axis. In the experiments, the feedback current to current control is the estimated current i_{b_est}.

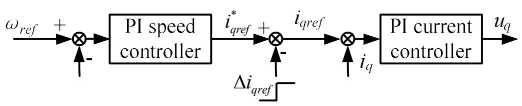

Fig.4 Diagram of speed loop with step disturbance in i_{qref}.

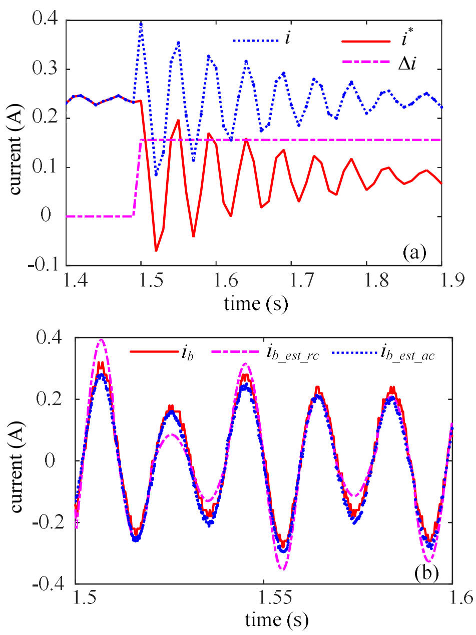

Fig. 5 Simulation results of the current estimation when subjected to a disturbance in i_{qref}: (a) the reference current, (b) the actuan and estimated currents of i_b.

Fig. 5 (a) gives the curves of disturbance current and the reference current of current controller. Fig. 5 (b) gives the curves of measured current i_b (solid line), the estimated value using reference current ($i_{b\_est\_rc}$, dotted line), the estimated value using the proposed amplitude tracing method ($i_{b\_est\_ac}$, point line). From the Fig. 5, we can find that the estimated error of the proposed estimating method is smaller than the estimating method based on the reference current, when there is big change in reference current.

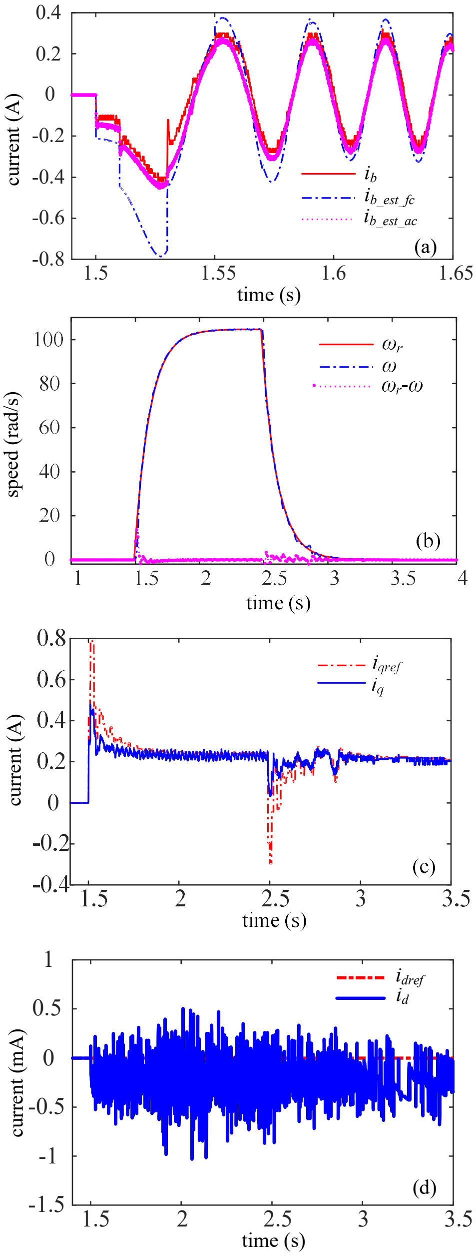

Fig. 6 Simulation results under step speed response: (a) actual and estimated current of b-phase, (b) reference and actual rotor speed, (c) q-axis current, and (d) d-axis current.

B. Response of Step speed

A step change of speed command from 0 to 100 rad/s is applied at 1.5s and return to 0 rad/s at 2.5s. During experiment a constant static friction (0.25 Nm) is added to motor. The actual and estimated current of i_b are shown in Fig. 6 (a). The estimated value i_{b_est} can track the actual very well except the sudden change of i_{q_ref} at 1.5s and 2.5s (as shown in Fig. 6 (c)). However, the speed tracking error is in the acceptable range, as shown in Fig. 6 (b). Fig. 6 (c) and Fig. 6 (d) are the reference current and actual currents of q-phase and d-phase.

C. Response of Ramp speed

The response result of ramp speed is given in Fig. 7. The reference speed (ω_r) is changed from 0 to 56.7 rad/s following a ramp gradually. Meanwhile, the load of motor is also gradually increased form 0 to 0.25Nm. The reference speed is maintained constant from 3 s. The actual and estimated current of i_b are given in Fig. 7 (a), which shows almost negligible estimation error of current. The reference speeds, actual rotor speeds and the speed tracking error are shown in Fig. 7 (a), which shows the good tracking ability using the estimated value of i_b.

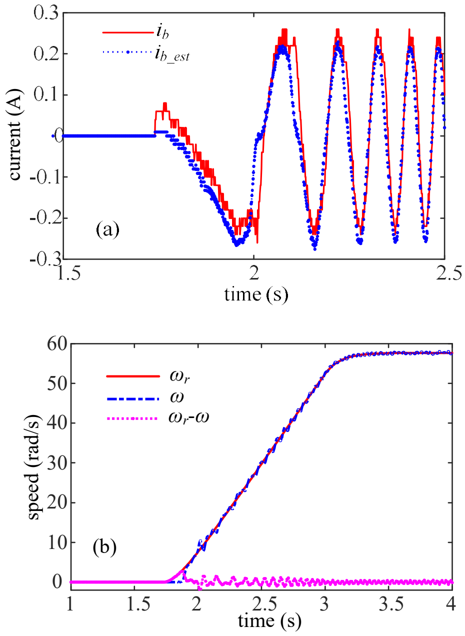

Fig. 7 Simulation results under ramp response: (a) actual and estimated current of i_b, (b) reference and actual rotor speed.

D. Load disturbance

The control performance of system under a disturbance of load (τ_L) is presented here. The drive system is working under a steady state with the given load of -2Nm. At 3.5 s, a step disturbance ($\Delta\tau_L$) is added to motor (i.e., $\Delta\tau_L$ = 0.2Nm). The added disturbance is eliminated at 3.51s. Thus, the system is subjected to a 10% disturbance to study the behavior of the current estimation mechanism. Fig. 5 shows the corresponding simulation results. From Fig. 8 (a), it can be observed that estimated value of b-axis current follows the actual current with negligible error. Fig. 8 (b) shows the current-vector trajectory in α- β stationary reference during 3.45~3.55s. Fig. 8 (b) gives the reference current and actual current in q-axis.

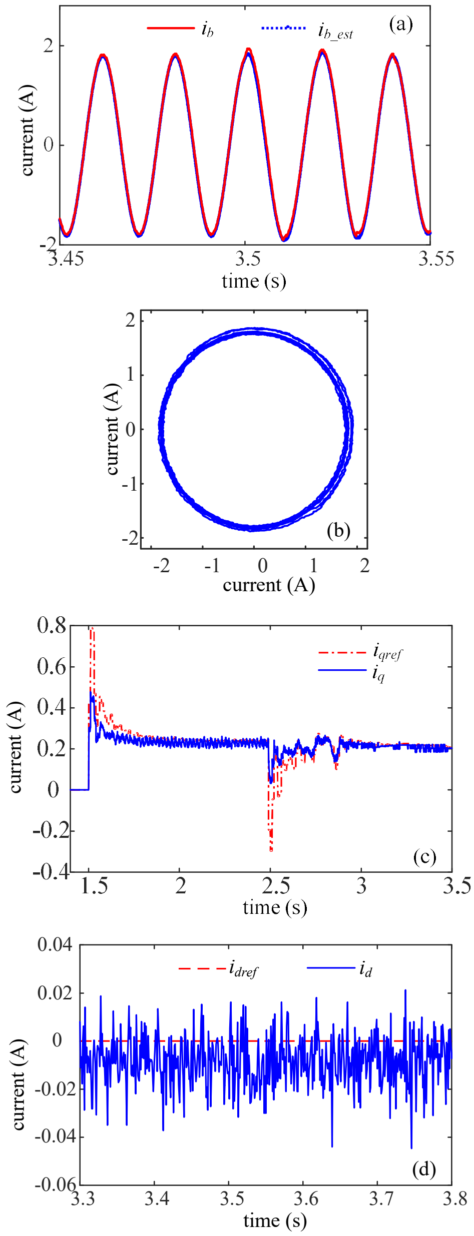

Fig. 8 Control performance using estimated current when subjected to a disturbance: (a) simulated real and estimated current of b-axis, (b) the current-vector trajectory in α-β stationary reference, (c) reference current and simulated real current in q-axis, (d) reference current and simulated real current in q-axis.

V. Conclusion

A simplified estimation method of phase current of PMSM is proposed in this paper. This new method bases on the current message of another current sensor and the angle message of motor rotor. A PI control has been used to realize the amplitude estimation of the measured current. Thus, the estimated current can get according trigonometric functions and can be used in the vector control of motor driver. The newly proposed method does not relay on the model and parameters of PMSM and not sensitive to the disturbance of load torque and the reference current. The method has been tested using MATLAB/SIMULATION software, and the experimental results have illustrated the feasibility and robustness of the proposed method.

Ⅶ. ACKNOLEDGEMENTS

This work is supported by the Self-planned Task (No. SKLRS201801C) of State Key Laboratory of Robotics and System (HIT), the Heilongjiang Postdoctoral Scientific Research Foundation (No. LBH-Q18059) and the Fundamental Research Funds for the Central Universities (Grant No.Hit.NSRIF.2015059).

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