A Novel Discrete-Time Predictive Current Control for PMSM

Jung-Won Sun*, Jin-Ho Suh*, Young-Jin Lee**, and Kwon-Soon Lee***

* Department of Electrical Engineering, Dong-A University
840, Hadan-dong, Saha-gu, Busan, 604-714, Korea
Selove783@hanmail.net , suhgang@hanmail.net
** Dept. of Electrical Instrument and Control, Korea Aviation Polytechnic College
438 Egeum-dong, Sachon City, Kyungnam, 664-180, Korea
airlee@kopo.or.kr
*** Division of Electrical, Electronic, and Computer Eng., Dong-A University
840, Hadan-dong, Saha-gu, Busan, 604-714, Korea
kslee@daunet.donga.ac.kr

Abstract: In this paper, we propose a new discrete-time predictive current controller for a PMSM(Permanent Magnet Synchronous Motor). The main objectives of the current controllers are to ensure that the measured stator currents tract the command values accurately and to shorten the transient interval as much as possible, in order to obtain high-performance of ac drive system.

The conventional predictive current controller is hard to implement in full digital current controller since a finite calculation time causes a delay between the current sensing time and the time that it takes to apply the voltage to motor. A new control strategy in this paper is seen the scheme that gets the fast adaptation of transient current change, the fast transient response tracking and is proposed simplified calculation. Moreover, the validity of the proposed method is demonstrated by numerical simulations and the simulation results will be verified the improvements of predictive controller and accuracy of the current controller.

Keywords: PMSM, Predictive Current Control, MRAC(Model Reference Adaptive Control), SVPWM

1. INTRODUCTION

The main objectives of the current controller are to ensure that the measured stator currents track the required values accurately and to shorten the transient interval as much as possible. Until the present, various current controllers are proposed. Like the following those, generally, we classify into the four main type of current control schemes [1][2].

(1) *Hysteresis Control*: The hysteresis current control method has advantages such as a fast transient response and simple circuits in implementation. But it shows high and non-constant switching frequency inthe inverter. By the result, it generates the harmonics and reduces the length of circuit.

(2) *Ramp Comparison Control*: The Ramp Comparison Current Control method has the advantages of limiting the maximum inverter switching frequency and producing well-defined harmonics. Even though the controller has optimized gains, there are magnitude and phase delay errors in steady state since the control method has low pass filter characteristics.

(3) *Synchronous Frame Proportional Integer Control*: In addition to the rotor synchronous frame PI control, compensation of the back EMF and cross-coupling terms gives fast transient response and zero steady-state error irrespective of operating conditions.

(4) *Predictive Control*: In the predictive control scheme, the switching duties of the inverter switches are determined by calculating the required voltages forcing the motor phase currents to follow corresponding references. If the motor and inverter parameters are well known, the predictive controller shows the fast transient response and no steady state error. But If we do not know those, the predictive current controller is not implemented well.

With the development of microprocessor technology, most current control schemes can be implemented in full digital systems.

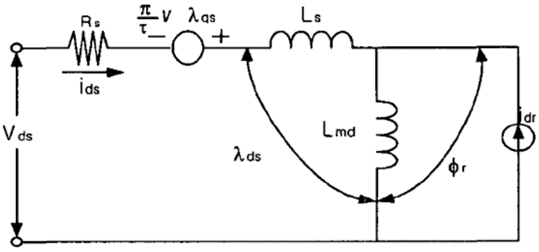
The objectives of this paper is that obtain the good result than conventional current control method with the implement of the predictive current controller that is based on discrete-model of PMSM(Permanent Magnet Synchronous Motor). And in accordance with the general tendency of the sensorless, we will obtain the angular velocity of the mover without the sensor. The method is that use the MRAC(Model Reference Adaptive Control) of simple inputs.

In this paper, we will use the Simulink of the MATLAB Program to prove the feasibility and effectiveness of the system with proposed predictive current controller and MRAC. Especially, we implemented the study using a prototype 750W PM-SM servo drive system in this paper.

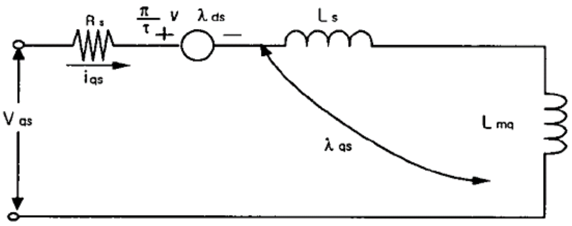
2. SYSTEM DESCRIPTION

2.1 The voltage equation of PMSM

The equivalent circuit of PMSM shows in Fig. 1.



(a) d-axis circuit



(b) q-axis circuit
Fig. 1 The equivalent circuit of PMSM

In the Fig. 1, the motor losses (copper, core, and mechanical), magnet saturation, air gap space harmonics and harmonic components of voltage and current are neglected in order to simplify the analysis.

In order to simulate, the voltage equation of PMSM in the synchronous reference can be expressed as follows:

$$V_{ds} = R_s i_{ds} + p\lambda_{ds} - \omega_r \lambda_{qs} \tag{1}$$

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds} \tag{2}$$

with

$$\omega_e = \left(\frac{\pi}{\tau}\right)v$$

$$\lambda_{qs} = \left(L_s + L_{mq}\right) i_{qs}$$

$$\lambda_{ds} = (L_s + L_{md}) i_{ds} + \varphi_r$$

where

i_{ds}, i_{qs} : d-q axis current ;
V_{ds}, V_{qs} : d-q axis voltage ;
$\phi_{r:}$: flux linkage due to permanent magnet per phase ;
R_s : resistance of primary ;
L_s : self-inductance of primary ;
L_{md}, L_{mq} : d-q axis component of magnetizing inductance ;
ρ : d/dt ;
ω_e : electrical angular velocity ;
τ : pole pitch ;
v : velocity ;

If the voltage equation is arranged, the equation can be expressed as follows [4].

$$V_{ds} = R_s i_{ds} + L_q \frac{d}{dt} i_{ds} - L_q i_{qs} w_e \tag{3}$$

$$V_{qs} = R_s i_{qs} + L_d \frac{d}{dt} i_{qs} + L_q w_e + \phi_{PM} \tag{4}$$

From the above voltage equation, the discrete-model voltage equation of a PM Synchronous Motor is described as follows.

$$\begin{aligned} V_{qs} &= R_s i_{qs}(k) + \frac{L_q}{T_s}(i_{qs}(k+1) - i_{qs}(k)) \\ &\quad + L_d \omega_e i_{ds}(k) + \phi_{PM}\omega_e \end{aligned} \tag{5}$$

$$\begin{aligned} V_{ds} &= R_s i_{ds}(k) + \frac{L_d}{T_s}(i_{ds}(k+1) - i_{ds}(k)) \\ &\quad - L_q i_{qs}(k)\omega_e \end{aligned} \tag{6}$$

where
T_s : sampling time ;

This equation is the discrete-model voltage equation of conventional predictive current controller

2.2 Space Vector PWM

The voltage space vector corresponding to eight switching states of the inverter are shown in Fig. 2. The section of the voltage space vector is divided into six sections. And the magnitude of each voltage vector that corresponds to six active states is 2/3 Vdc, and these vectors form a hexagon. And the voltage vectors u_0 and u_7 that correspond to freewheeling states are zero voltage vectors.

The Relation between voltage space vector and voltage commands in dq-axes is shown in Fig. 3. The V_{dc} is the dc link voltage, and the V_s is the magnitude of the space V_s. The V_s of voltage commands is calculated from the V_d^*, V_q^*, and θ_e.

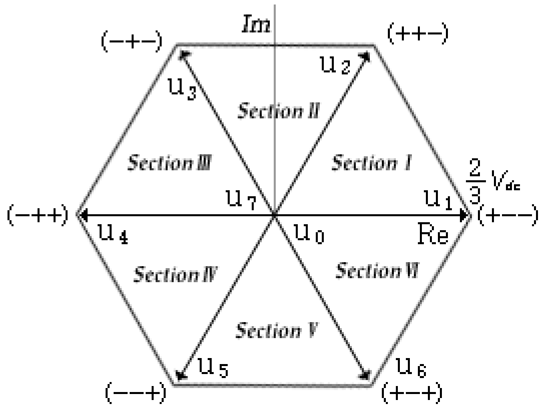


Fig. 2 Switching Voltage vectors of the three-phase inverter

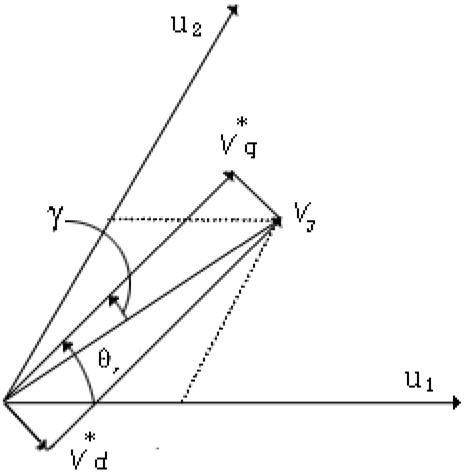


Fig. 3 Relation between voltage space vector and voltage commands in d-q axes
(when the space vector is in section Ⅰ)

In order to perform the SV-PWM(Space Vector Pulse Width Modulation), we need the following sequence. Here, we will discuss the Ⅰ Section.

In the first time, we must select where the command voltage is existed. If the command voltage is putted in the Ⅰ section, it is that satisfy as followings or if it don't satisfy the followings, command voltage is in the other section. And it must find a satisfactory section, immediately.

$$V_{\beta s}^* > 0 \quad \text{and} \quad \sqrt{3}\, V_{\alpha s}^* - V_{\beta s}^* > 0 \tag{7}$$

Next time, the decision of switching time is as follows:

$$T1 = \frac{\sqrt{3}T_s}{V_{dc}}\left(\frac{\sqrt{3}}{2}V_{\alpha s}^* - \frac{1}{2}V_{\beta s}^*\right) \tag{8}$$

$$T2 = \frac{\sqrt{3}T_s}{V_{dc}}(V_{\beta s}^*) \tag{9}$$

$$T3 = T_s - (T1 + T2) \tag{10}$$

And, the switching function of the Ⅰ section is described as Table 1. The symmetrical switching function has various advantages. Especially, in the inverter, the scheme of PWM is important elements of PMSM, because the scheme affects the inverter deeply.

Various PWM schemes have been proposed. But the SP-PWM is known as a good scheme for a response of transient current controller. This has advantages of much scopes of linear control, the disturbance of low harmonics, and the response of rapid transient.

Table 1 The switching function of section Ⅰ

Section	Switching Function	On mode			Off mode		
		$\frac{T_0}{2}$	$T1$	$T2$	$\frac{T_0}{2}$	$T1$	$T2$
Section Ⅰ	T_a	1	0	0	1	1	1
	T_b	1	1	0	1	1	0
	T_c	1	1	1	1	0	0

2.3 Timing Sequence of the current Control

The time sequence of the current control is described as follows:

(1) In the instance of (k)th, the process of control is started, and sampled DC link voltage, and rotor location.

(2) In the gray section between (k)th and (k+1)th, it is expressed calculating the time of current control.

(3) Before (k+1)th signal, the output value of current control is recorded in the DSP

(4) Between (k+1)th and (k+2)th, the phase voltage calculated in the previous period are applied to the motor through inverter.

(5) Repeat sequence 1~4.

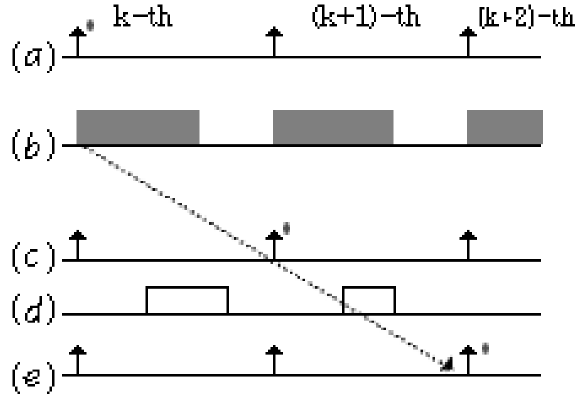


Fig. 4 Timing Sequence of current controller

In spite of existence of delay between starting time of input and time applied voltage in the motor, we use the predictive current control, because this has the advantage of the predictive outputs. Here, this means that the predictive controller has one step of the rapid outputs.

2.4 Proposed predictive current controller

In generally, eq. (5) and eq. (6) is described by

$$I(k+1) = AI(k) + B(V(k) - E(k)) \tag{11}$$

Here, parameter values are described as follows, respectively.

$$A = \begin{bmatrix} 1 - \frac{T_s R_s}{L_q} & 0 \\ 0 & 1 - \frac{T_s R_s}{L_d} \end{bmatrix}, \quad B = T_s \begin{bmatrix} \frac{1}{L_q} & 0 \\ 0 & \frac{1}{L_d} \end{bmatrix} \tag{12}$$

$$E(k) = \begin{bmatrix} E_q(k) \\ E_d(k) \end{bmatrix} \tag{13}$$

$$E_d(k) = -L_s w_e i_{qs}(k) \tag{14}$$

$$E_q(k) = L_s w_e i_{ds}(k) + \phi_{PM} w_e \tag{15}$$

where

E_d, E_q : Back-EMF of d-q axes

Moreover, ω_e and ϕ_{PM} can be considered as a regular constant in sampling period between (k)th and (k+1)th.

Namely in comparison between proposed predictive current controller and the conventional predictive current controller, the different point is that the back-EMF is treated as the constant when it is sampled. By the above description, the system is simplified.

2.5 Estimating of the Back-EMF

We will estimate the Back-EMF to simplify the predictive current controller and reduce the cost in the circuit.

To estimate the Back-EMF (E_d, E_q), the control method of sensorless using MRAC is described by the following schematic diagram as shown in Fig. 5.

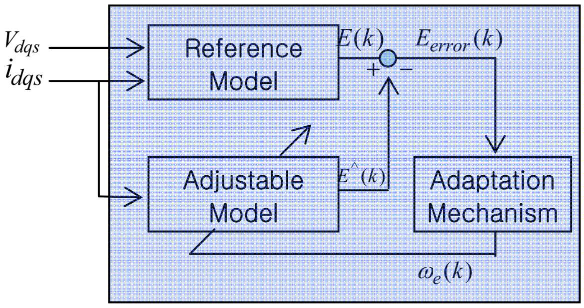


Fig. 5 Structure of MRAC for Back-EMF

The stator current, voltage, the reference current, and the angular velocity are embodied as inputs of the reference model and the adjustable model. And the reference model and the adjustable model generate the reference Back-EMF and the adjustable Back-EMF, respectively. The difference between the Back-EMF of the reference model and the adjustable model is the $Error(k)$.

The $Error(k)$ is used as input of the adaptive mechanism, and the ω_e of estimating angular velocity is generated from the adaptation mechanism. This estimated velocity is entered again as feedback inputs in the adjustable model. And, if the error is generated by calculating between the reference model and adjustable model, the error approaches the zero by the controller. The MRAC generates the accuracy ω_e of estimated velocity. Here, ω_e can be treated as the regular constant in sampling transient. Therefore, the estimating Back-EMF equation of the reference model is described as follows, from eq. (5) and eq. (6) [5].

$$E_{qs}(k) = V_{qs}(k) - L_s \frac{i_{qs}(k+1) - i_{qs}(k)}{T_s} - R_s i_{qs}(k) \quad (10)$$

$$E_{ds}(k) = V_{ds}(k) - L_s \frac{i_{ds}(k+1) - i_{ds}(k)}{T_s} - R_s i_{ds}(k) \quad (11)$$

The estimating Back-EMF equation of the adjustable model is described as follows from equation (14) and (15)

$$E_q(k) = L_s w_e i_{ds}(k) + \phi_{PM} w_e \quad (16)$$

$$E_d(k) = -L_s w_e i_{qs}(k) \quad (17)$$

And the estimating angular velocity is described as follows from stability of the adaptation mechanism.

$$w_e = (K_1 + \frac{K_2}{s}) E_{error}(k) \quad (18)$$

We can obtain the Back-EMF with estimating angular velocity in MRAC.

2.6 The whole system

The whole system is described as Fig. 6. The reference current and voltage is entered in the predictive current controller.

The output is entered in the space vector PWM. And the Back-EMF is calculated from the output of MRAC, and the reference current and voltage. The output is entered in the predictive current controller.

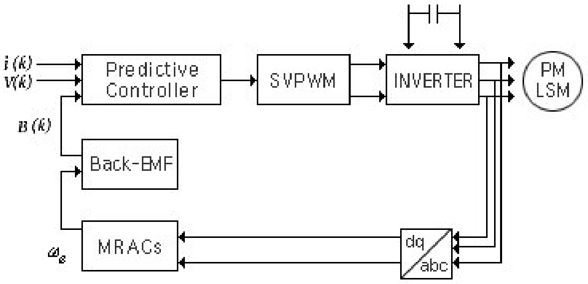


Fig. 6 The whole system

3. Numerical Simulations

To ensure the propriety of the proposed predictive current control and MRAC, the numerical simulations are implemented in simulink of the MATLAB Program. The result of simulation is shown as Fig. 7, Fig. 8, and Fig. 9. The three-phase current waveform is shown in Fig. 7. And between 0 second and 0.005 second, the waveform is uncertain. But after 0.005 second, the waveform is stabilized.

The d-q axes current waveform is shown in Fig. 8. This is shown state like the three-phase current waveform. The angular velocity waveform is shown in Fig. 9. Here, the reference velocity is 1200rpm. After two second, the real velocity is approached in a reference velocity.

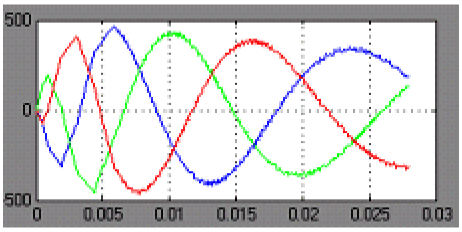


Fig. 7 Three phase current waveform

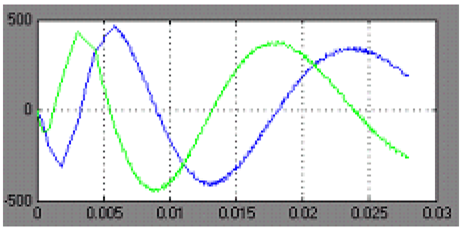


Fig. 8 d-q current waveform

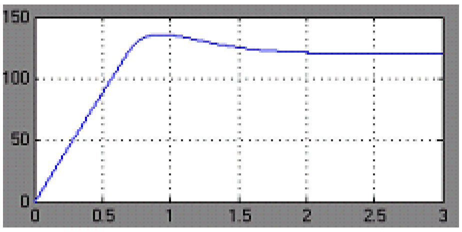


Fig. 9 Velocity waveform

4. CONCLUSION

This paper presents the predictive current controller estimating the Back-EMF, based on a discrete model of PMSM, under the assumption having regular constant Back-EMF during the sampling. We can get a little delay between sensed time of current and applied time of voltage in motor. In the implement of the stable state and transient state, we can also see the good characteristic.

Here, the response of the current is not compare with other predictive current control, and the response of real velocity is lately approached. Hereafter, we will compare the other current controller and elevate the response of real velocity.

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