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교류전동기 벡터제어를 위한 전류 측정오차의 저감에 관한 연구

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Diminution of Current Measurement Error for Vector Controlled AC Motor Drives

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ABSTRACT

In order to achieve high performance vector control, it is essential to measure accurate ac current. The errors generated from current path are inevitable, and they could be divided into two categories: offset error and scaling error. The current data including these errors cause periodic speed ripples which are one and two times of stator electrical frequency respectively. Since these undesirable ripples bring about bad influences to motor driving system, a compensation algorithm must be needed in the control algorithm of the motor drive.

In this paper, a new compensation algorithm is proposed. The signal of the integrator output of the d-axis current regulator is chosen and processed to compensate the current measurement errors. The compensation of the current measurement errors is easily implemented to smooth the signal of the integrator output of the d-axis current regulator by subtracting the DC offset value or rescaling the gain of the hall sensor.

Therefore, the proposed algorithm has several features: the robustness of the variation of the mechanical parameters, the application of the steady and transient state, the easy implementation, and less computation time.

1. Introduction

Recently, the vector control is essential to operate AC motor. In the vector control, precise current measurement is very important[1-2]. Stator currents are measured through hall sensors, low pass filters and A/D converters. Because of the non-linearity of the hall sensor, thermal drift of analog elements, and the missing code of the A/D converters, the errors generated from current path are inevitable. Fig.1 summaries the types of errors in the digital AC motor drive system[3]. This type of errors will appear as offset and scaling error in the end.

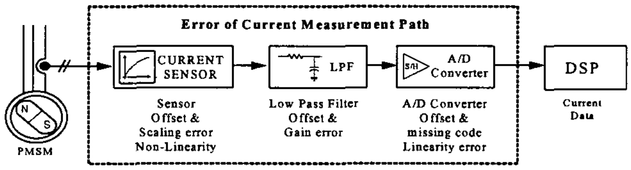


Fig. 1 Error path of current measurement.

When the stator currents include the offset and scaling errors, torque pulsation occurs corresponding to one and two times of stator electrical frequency respectively. This results in the deterioration of the performance of the motor drive system. So, the recent studies have reported that the undesirable periodic ripple element was related by the error in current measurement.

In this paper a new compensation method is proposed. The main contribution of this paper introduces the signal of the integrator output of the d-axis current regulator to compensate for the errors of the current measurement. Usually the d-axis current comment is zero or constant to acquire the maximum torque or unity power factor in the ac drive system, and the output of the d-axis current regulator is nearly zero or constant as well. If the stator currents include the offset and scaling errors, the signal of the integrator output of the d-axis current regulator also has the ripple. The compensation of the current measurement errors is easily implemented to smooth the signal of the integrator output of the d-axis current regulator by subtracting the DC offset value or rescaling the gain of the hall sensor.

2. The Effect of Current Measurement Error[4]

2.1 Effect of offset error

The offset error, which may be caused by a potential imbalance of a sensor device and measurement path, the effects of the thermal drift of analog devices , the switching noise, and etc. is inevitable.

The error of offset can be expressed in an actual 3 phase system by (1).

$$I_{as-sens} = I_{as} + \Delta I_{as}$$
$$I_{bs-sens} = I_{bs} + \Delta I_{bs} \qquad (1)$$
$$I_{cs-sens} = -(I_{as-sens} + I_{bs-sens})$$

From (1) the measured synchronous d-q axis currents can be calculated as follows:

$$I^e_{ds-sens} = I^e_{ds} + \Delta I^e_{ds}$$
$$I^e_{qs-sens} = I^e_{qs} + \Delta I^e_{qs} \qquad (2)$$

where

$$\Delta I^e_{ds} = \Delta I_{as}\cos\theta_e + \frac{1}{\sqrt{3}}(\Delta I_{as} + 2\Delta I_{bs})\sin\theta_e \qquad (3)$$

$$\Delta I^e_{qs} = -\Delta I_{as}\sin\theta_e + \frac{1}{\sqrt{3}}(\Delta I_{as} + 2\Delta I_{bs})\cos\theta_e \qquad (4)$$

ΔI^e_{ds} and ΔI^e_{qs} contain the ripple corresponding to the fundamental of the stator electrical frequency.

2.2 Effect of scaling error

The scaling error may be caused by non-linearity of the current sensor itself, the matching circuit between the current sensor and A/D input, the missing code and non-linearity of an A/D converter[9].

Usually the d-axis current command is zero or constant to obtain maximum torque in a constant torque region. If the stator currents contain the scaling error, the stator currents can be expressed as (5). Where K_a and K_b denote the scale factor of a, b phase current respectively. The minus sign merely reflects the reference angle of a-b phases.

$$I_{as-sens} = -K_a I\sin\theta_e$$
$$I_{bs-sens} = -K_b I\sin(\theta_e - \frac{2}{3}\pi) \qquad (5)$$

From (5) the measured synchronous d-q axis currents can be acquired as follows

$$\Delta I^e_{ds-scale} = I^e_{ds-sens} - I^e_{ds}$$
$$= \frac{(K_b - K_a)}{\sqrt{3}} I\sin(2\theta_e + \frac{\pi}{6}) + \frac{(K_b - K_a)I}{2\sqrt{3}} \qquad (6)$$

$$\Delta I^e_{qs-scale} = I^e_{qs-sens} - I^e_{qs}$$
$$= \frac{(K_b - K_a)}{\sqrt{3}} I\sin(2\theta_e + \frac{\pi}{3}) + \frac{(K_a + K_b)I}{2} \qquad (7)$$

As known from $\Delta I^e_{ds-scale}$ and $\Delta I^e_{qs-scale}$, d-q axis currents contain the ripple corresponding to two times ($2f_e$) of the stator electrical frequency.

3. The Compensation Method For Current Measurement Error

3.1 Analyzing the signal of the integrator output of the d-axis current regulator

If the stator currents include the offset and scaling errors, the motor speed has the ripple related to one and two times of the stator electrical frequency respectively. The signal of the integrator output of the d-axis current regulator also has the ripple as the motor speed does. This signal can be derived by integrating the sum of (3) and (6) as follows in (8):

$$K_i \int_0^t (i^{e*}_{ds} - i^e_{ds-sens})dt = -K_i \int_0^t \Delta i^e_{ds} dt \qquad (8)$$

As known from (3) and (6), (8) contains the ripple corresponding to one, two and six times of the stator electrical frequency. Six times frequency ripple is the effect of the dead time of the switching device[10 11]. In order to remove or ignore the dead time effect, dividing (8) into 6 segments during one cycle of the electrical angle(θ_e), and integrating 6 segments result in the elimination of that effect.

3.2 Proposed Compensation Method

A. Offset Errors Compensation.

Fig. 2 shows the results of two cases. One case is dividing (8) into two segments ($sec1$ and $sec2$) and integrating as known in Fig.2 (a). And the result of calculation of $sec1$ and $sec2$ is shown in (9) and (10) respectively.

$$sec1 = \int_0^{\pi}\int_0^t -K_i \Delta I^e_{ds} dt d\theta_e \qquad (9)$$

$$sec2 = \int_0^{\pi}\int_0^t -K_i \Delta I^e_{ds} dt d\theta_e \qquad (10)$$

The difference (ϵ_1) reflects the existence of a-phase offset error (ΔI_{as}), and is (11) as follows:

$$\epsilon_1 = sec1 - sec2 \qquad (11)$$

This error (ϵ_1) is easily removed or compensated by equalizing the integral values between two segments.

The other case is dividing (8) into six segments (sec I ~secVI) and integrating as shown in Fig.2 (b) and (c).

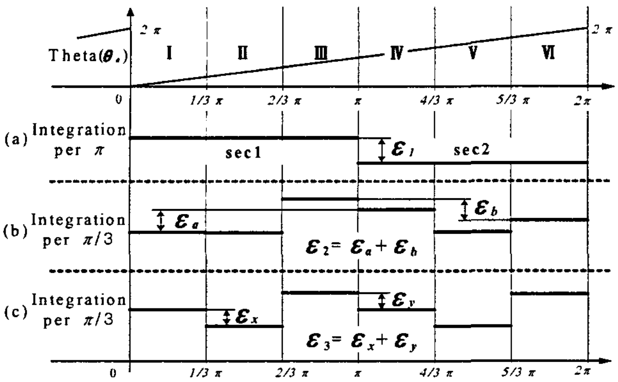


Fig. 2 Each error of current analyzed for compensation.

Nevertheless the signal of the integral output of d-axis current regulator has the offset error, sec I, secIII, secIV and secVI have the different values as shown in Fig.2 (b), and (12).

$$secI = \int_0^{\frac{\pi}{3}}\int_0^t -K_i\Delta I_{ds}^e dt d\theta_e\ , secIII = \int_{\frac{2\pi}{3}}^{\pi}\int_0^t -K_i\Delta I_{ds}^e dt d\theta_e$$
$$secIV = \int_{\pi}^{\frac{4\pi}{3}}\int_0^t -K_i\Delta I_{ds}^e dt d\theta_e ,\ sec\ VI = \int_{\frac{5\pi}{3}}^{2\pi}\int_0^t -K_i\Delta I_{ds}^e dt d\theta_e \qquad (12)$$

The summation(ϵ_2) between ϵ_a and ϵ_b explains the existence of b-phase offset error(ΔI_{bs}) as shown in Fig.2 (b), and (13).

$$\epsilon_a = \sec IV - \sec I\ ,\ \epsilon_b = \sec III - \sec VI$$
$$\epsilon_2 = \epsilon_a + \epsilon_b \qquad (13)$$

If offset errors (ϵ_1 and ϵ_2) are completely compensated or removed, each segment shows values as (14) respectively. (14) is always satisfied although scaling errors are in the signal of the integrator output of the d-axis current regulator.

$$\sec I = \sec IV$$
$$\sec II = \sec V \qquad (14)$$
$$\sec III = \sec VI$$

B. Scaling Errors Compensation.

If the scaling factors (K_a and K_b) of a- and b-phase have the same value, (6) and (7) are zero or vanished. And (15),(16)and(17) reflect the existence of scaling errors.

$$secI = \int_0^{\frac{\pi}{3}}\int_0^t -K_i\Delta I_{ds-scale}^e dt d\theta_e \qquad (15)$$

$$secII = \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}}\int_0^t -K_i\Delta I_{ds-scale}^e dt d\theta_e \qquad (16)$$

$$secIII = \int_{\frac{2\pi}{3}}^{\pi}\int_0^t -K_i\Delta I_{ds-scale}^e dt d\theta_e \qquad (17)$$

The summation (ϵ_3) between $\epsilon_x$and $\epsilon_y$explains the existence of scaling errors between a- and b-phase as shown in Fig.2 (c), and (18).

$$\epsilon_x = \sec I - \sec II\ ,\ \epsilon_y = \sec III - \sec I$$
$$\epsilon_3 = \epsilon_x + \epsilon_y \qquad (18)$$

Scaling error (ϵ_3) is easily removed or compensated by making zero. The compensation is carried out about two phases simultaneously until $\epsilon_3 = 0$.

C. Implementation of the proposed compensation algorithm

Fig.3 shows the main conceptual block diagram of the proposed compensation method.

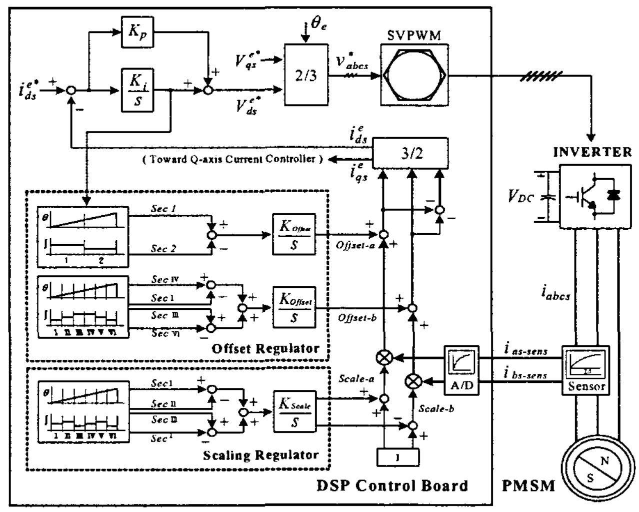


Fig. 3 Main block diagram of the proposed compensation scheme

The signal of the integrator output of d-axis current regulator is used to the input of the proposed compensation algorithm. This algorithm consists of offset and scaling part. The integral outputs of offset part are (11) and (13). And these terms are the input of I-type (Integral-type) controller (K_{offset}/S). Two I-type controllers of offset part force ϵ_1 and ϵ_2 to be zero. And ϵ_3 of scaling error is the input of I-type controller. Also I-type of scaling part forces ϵ_3 to be zero. the compensation direction corresponds to table 1. The compensating gains (K_{offset} and K_{scale}) of the offset and scaling errors can be chosen between 0 and 1. The smaller gain, the slower response, but more accurate compensation current can be achieved. In this paper, $K_{offset} = 0.1$ and $K_{scale} = 0.05$ are chosen for stable operation. The compensating action is finally achieved by (19) from output($Offset\_a, Offset\_b, Scale\_a, Scale\_b$) of I-type controller.

$$I_{as} = I_{as-sens} \times Scale\_a + Offset\_a$$
$$I_{bs} = I_{bs-sens} \times Scale\_b + Offset\_b \qquad (19)$$

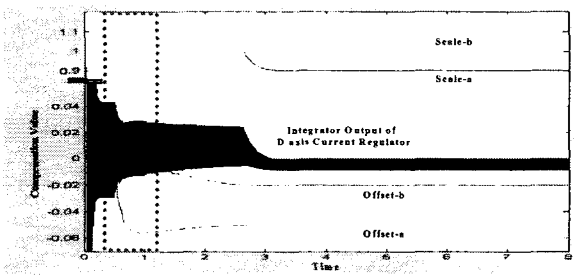
Table 1 Compensation direction of proposed algorithm.

Value	Error of Integral Value	Error of Measured Current	Direction of Compensation
$Offset\_a$	$\epsilon_1 > 0$	$\Delta I_{as} < 0$	(+)
	$\epsilon_1 < 0$	$\Delta I_{as} > 0$	(−)
$Offset\_b$	$\epsilon_2 > 0$	$\Delta I_{bs} < 0$	(+)
	$\epsilon_2 < 0$	$\Delta I_{bs} > 0$	(−)
$Scale\_a$	$\epsilon_3 > 0$	$K_a < K_b$	(+)
	$\epsilon_3 < 0$	$K_a > K_b$	(−)
$Scale\_b$	$\epsilon_3 > 0$	$K_a < K_b$	(−)
	$\epsilon_3 < 0$	$K_a > K_b$	(+)

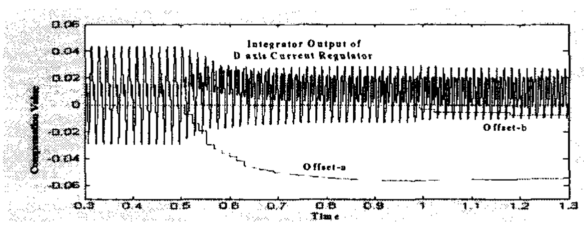
4. Simulation

The simulation of the proposed algorithm was performed by using MATLAB Simulink[12]. The current errors of offset and scaling are given, $\Delta I_{as} = 0.05\,[A]$, $\Delta I_{bs} = 0.02\,[A]$, $K_a = 1.1$ and $K_b = 0.9$ respectively in this simulation.

Fig.4 shows the simulation waveforms of the integrator output of the d-axis current regulator, and the starting time of the compensation is at 0.5[sec].



(a) Ripple reduction with the proposed compensation scheme



(b) Extension of (a) between 0.3[sec] and 1.3[sec]

Fig. 4 Simulation results

5. Experimental Results

The experimental result is obtained under the each error condition of $\Delta I_{as} = 0.05\,[A]$, $\Delta I_{bs} = 0.02\,[A]$, $K_a = 1.2$ and $K_b = 0.8$. Fig. 5 shows the steady state characteristics of the motor speed and the integral values of 6 segments before the compensation. The maximum speed ripple is about 0.5[rpm] and there exist undesirable $1f_e$ and $2f_e$ of the speed ripples as shown in FFT analysis.

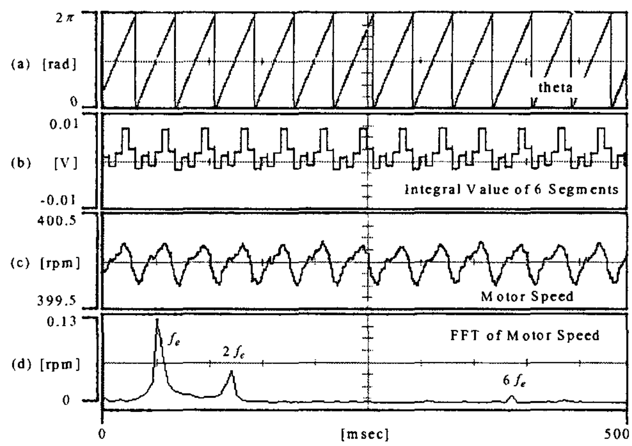


Fig. 5 Steady-state characteristics without compensation scheme

Fig. 6 shows the process of the compensation of current measurement errors. The ripple of Fig.6(c) is diminished by a method that looks for the compensating value in process.

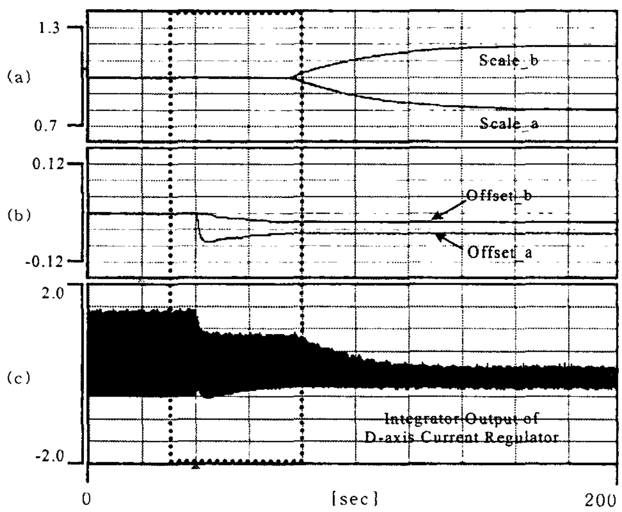


Fig. 6 Characteristics of compensating operation after flag-on

After the compensation by the proposed method, speed ripples are eliminated almost completely as shown in Fig. 7. $6f_e$ shows the influence of the dead time. and the effect will not be mentioned in this paper.

Fig. 8 shows dynamic characteristics of current errors compensation in the transient state. From this experimental result the proposed compensation algorithm has the attractive feature of transient state operation.

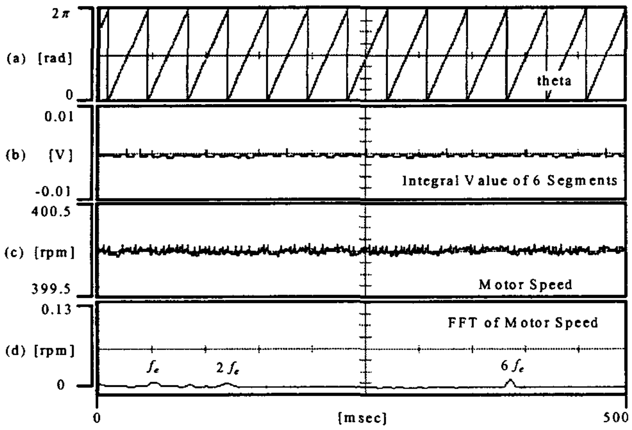


Fig. 7 Steady-state characteristics with proposed compensation scheme

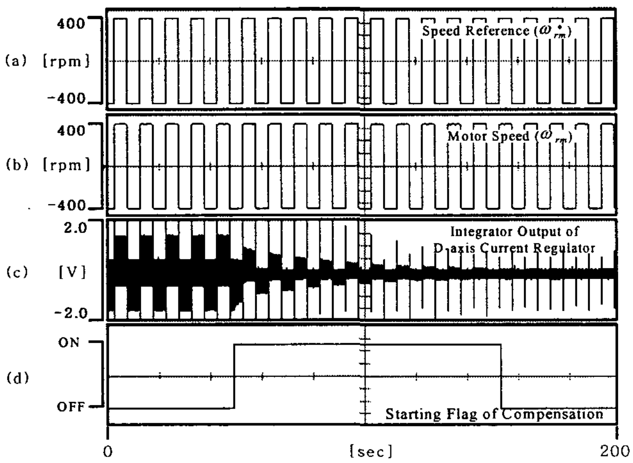


Fig. 8 Dynamic characteristics of compensation in the transient state

6. Conclusions

In the digital AC motor drive system, the torque pulsation is caused by the offset and scaling error of the stator currents. Thus without the proper compensation algorithm, higher performance vector control cannot be accomplished.

In this paper the new compensation algorithm was proposed. Through the simulation and experimentation the feasibility and effectiveness was verified. The main contribution of this paper introduces the signal of the integrator output of the d-axis current regulator to compensate the current errors. Usually the d-axis current comment is zero or constant to acquire the maximum torque or unity power factor in the ac drive system, and the output of the d-axis current regulator is nearly zero or constant as well.

Therefore the proposed algorithm has several features of the robustness of the variation of the machine variables, the application of the steady and transient state, the easy implementation, and requiring less computation time.

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