JPE 9-5-9

Compensation of Position Error due to Amplitude Imbalance in Resolver Signals

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ABSTRACT

This paper presents a compensation algorithm for position error due to an amplitude imbalance between resolver output signals. Resolvers are typically used to obtain absolute position information for motor drive systems in severe environments. Position error is caused by an amplitude imbalance of the resolver output signals. As a result, the *d*- and *q*-axis currents of synchronous reference frame have periodic ripples in the stator fundamental frequency in permanent magnet synchronous motor (PMSM) drive systems. Therefore, this paper proposes a compensation algorithm to reduce the position error generated by the amplitude imbalance. The proposed method does not require any additional hardware, and reduces computation time with a simple integral operation according to rotor position. In addition, the position error can be directly compensated for by the estimated position error. The effectiveness of the proposed compensation algorithm is verified through several simulations and experiments.

Keywords: Resolver, Amplitude imbalance, Position error, Ripples of the stator fundamental frequency, Integral operation

1. Introduction

Resolvers are commonly used in many areas including the automotive industry, especially in applications of electric power steering (EPS) and hybrid electric vehicles. Their robustness and reliability make them particularly well suited to harsh industrial environments [1],[2]. Resolver output signals contain angular position information that is obtained in digital form using a resolver-to-digital (R/D) converter. Several solutions for R/D conversion of resolver signals have been suggested [2-5]. These methods focus on ways to improve the measurement accuracy of the R/D converter. They are cost effective, reasonably accurate, and can be implemented using less hardware to reduce weight and size in limited space applications. Therefore, conventional tracking R/D converters generate position resolution and accuracy specifications under the assumption that ideal resolver signals are supplied to the converter. However, no resolver generates ideal signals, and thus accurate specifications from an R/D converter

Manuscript received Mar. 12, 2009; revised July 16, 2009.
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cannot be obtained in reality. Actual resolver signals have non-ideal characteristics such as amplitude imbalance, imperfect quadrature, inductive harmonics, and reference phase shift [6],[7]. Due to these non-ideal characteristics, the rotor position from an R/D converter is distorted. In particular, the amplitude imbalance between resolver output signals is the most dominant non-ideal characteristic [6]. It originates from the different turn ratios of the transformers, unbalanced excitation signals, and nonlinear characteristics of analog devices such as Op-Amp, low-pass filters. To solve non-ideal characteristics, a few approaches have been studied [6],[7]. In [6], most of these errors have been corrected, including those with an origin in the R/D converter. However, this method is very labor intensive, results in excessive signal processing and hardware. In [7], a method was proposed to reduce torque ripple caused by the amplitude imbalance. It needs ideal position information like that produced by a separate steering position sensor in order to obtain a sine table and corrected sine and cosine values for a transformation matrix.

This paper proposes a new compensation algorithm for position error due to an amplitude imbalance between resolver output signals. The effects of position error are analyzed by the *d*- and *q*-axis currents of the PMSM drive systems using the output signal of the R/D converter. As a result, the *dq*-axes currents of the synchronous reference frame have periodic ripples due to the position error caused by an amplitude imbalance. The proposed compensation algorithm is easily implemented by an integration operation according to the rotor position in a specified section. It also requires less computation time than other methods. The proposed algorithm is verified through simulations and experimental results.

2. Analysis of Position Error due to Amplitude Imbalance

2.1 Structure of a Resolver

A block diagram of a resolver is shown in Fig. 1. The resolver is basically a rotating transformer with one primary winding U_{ref}, and two secondary windings $U_{\sin}$ and $U_{\cos}$, as shown in Fig. 1 [1-7]. The primary winding is located on the rotor side. It is excited by a frequency of a few kHz. The secondary windings are placed at the stator and at the space of the quadrature. As a result, the output signals on the secondary windings are modulated with the amplitudes of sine and cosine waveforms according to the resolver shaft position θ. Therefore, rotor position information can be obtained by demodulation through a tracking loop of an R/D converter with secondary output signals.

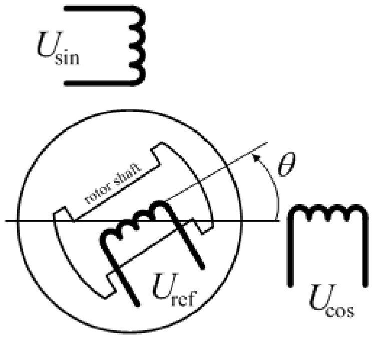

Fig. 1. Block diagram of a resolver.

2.2 Ideal R/D Conversion [6]

Fig. 2 shows the operational block diagram of an R/D converter, including demodulation and a feedback loop with speed/position calculation.

In Fig. 2, the two output signals of the resolver, $U_{\sin}$ and $U_{\cos}$ are written as:

$$U_{\sin} = KE \sin \omega t \sin \theta \tag{1}$$

$$U_{\cos} = KE \sin \omega t \cos \theta \tag{2}$$

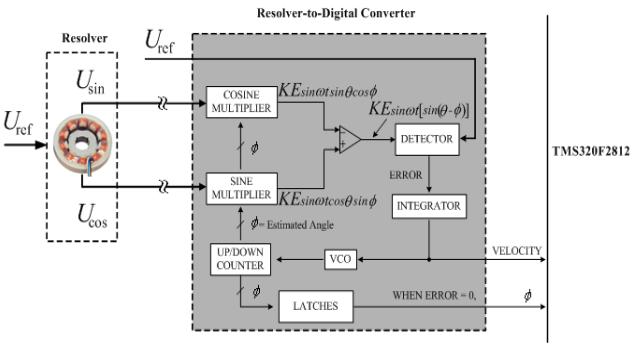

Fig. 2. Block diagram of a tracking loop of R/D converter.

where, K is the turn ratio of the rotating transformer, E is the rotor excitation amplitude, ω is the rotor excitation frequency and θ is the resolver shaft position.

First, input signals to the R/D converter, (1) and (2) are multiplied by $\cos\phi$ and $\sin\phi$, respectively. ϕ is the estimated rotor position in the R/D converter, as shown in Fig. 2. Second, the difference between the two signals can be represented by:

$$\begin{aligned} U'_{\sin-\cos} &= KE\sin\omega t[\sin\theta\cos\phi - \cos\theta\sin\phi] \\ &= KE\sin\omega t\sin(\theta-\phi) \end{aligned} \quad (3)$$

From (3), the error voltage, U'_{err} can be derived by:

$$U'_{err} = KE\sin(\theta-\phi) \quad (4)$$

If estimated rotor position ϕ is updated by a tracking loop of the R/D converter, U'_{err} is driven to zero. When this is done, the estimated position of the R/D converter, ϕ is forced to track the actual shaft position θ to obtain the zero position error. In an actual R/D converter, ϕ is recursively updated and is output in a digital format.

2.3 Non-ideal R/D Conversion with Amplitude Imbalance [6],[7]

The resolver output signals, including the amplitude imbalance, are shown in Fig. 3. In this case, the resolver outputs of the sine and the cosine voltages can be expressed as [6-7]:

$$U_{\sin} = KE\sin\omega t\sin\theta \quad (5)$$

$$U_{\cos} = KE(1+\alpha)\sin\omega t\cos\theta \quad (6)$$

where, α is the difference in amplitude between the two resolver outputs.

Therefore, the difference between the resolver output signals can be rewritten as:

$$U'_{\sin-\cos} = KE\sin\omega t[\sin\theta\cos\phi - (1+\alpha)\cos\theta\sin\phi] \quad (7)$$

As a result, the error voltage U'_{err} can be obtained by

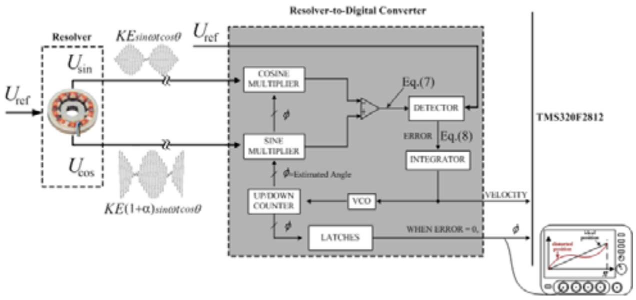

Fig. 3. Block diagram of R/D converter including the amplitude imbalance.

removing the excitation signal $\sin\omega t$ from (7):

$$U'_{err} = KE[\sin(\theta-\phi) - \alpha\cos\theta\sin\phi] \quad (8)$$

Driving the error voltage to zero, an R/D converter does not lead to $\theta = \phi$. However, by setting the above equation to zero, it is possible to find the position error $\theta_{err} = \theta - \phi$. The error component can be derived by:

$$\sin(\theta-\phi) = \alpha\cos\theta\sin\phi \quad (9)$$

In a real case, when α is small, the position error is also small which implies that $(\theta-\phi) = \theta_{err}$. Using these approximations, (9) can be represented by [6-7]:

$$\sin\theta_{err} \approx \theta_{err} = \frac{\alpha}{2}\sin 2\theta \quad (10)$$

As shown in (10), the amplitude imbalance of the resolver signal generates ripples of twice the resolver shaft position.

3. Effects of Resolver Position Error in PMSM Drives

The d- and q-axis currents of the stationary reference frame are given by:

$$i^s_{ds} = i_{as} = -I_m\sin\omega_e t \quad (11)$$

$$i^s_{qs} = \frac{1}{\sqrt{3}}(i_{bs} - i_{cs}) = I_m\cos\omega_e t \quad (12)$$

where, ω_e is the electrical angular frequency.

If there is a position error θ_{err} in the transformation matrix, the *d*- and *q*-axis currents of the synchronous reference frame can be derived by:

$$\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} = \begin{bmatrix} \cos(\theta_e+\theta_{err}) & \sin(\theta_e+\theta_{err}) \\ -\sin(\theta_e+\theta_{err}) & \cos(\theta_e+\theta_{err}) \end{bmatrix} \begin{bmatrix} -I_m \sin\omega_e t \\ I_m \cos\omega_e t \end{bmatrix} = \begin{bmatrix} I_m \sin\theta_{err} \\ I_m \cos\theta_{err} \end{bmatrix} \quad (13)$$

where, θ_e is the electrical rotor position.

As shown in (13), the ripples of the *d*- and *q*-axis currents are caused by position error. In this case, a transformation matrix which has an amplitude imbalance, α can be obtained as:

$$\begin{aligned} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} &= \begin{bmatrix} (1+\alpha)\cos\theta_e & \sin\theta_e \\ -\sin\theta_e & (1+\alpha)\cos\theta_e \end{bmatrix} \begin{bmatrix} -I_m \sin\omega_e t \\ I_m \cos\omega_e t \end{bmatrix} \\ &= I_m \begin{bmatrix} -(1+\alpha)\cos\theta_e \sin\theta + \sin\theta_e \cos\theta_e \\ \sin^2\theta_e + (1+\alpha)\cos^2\theta_e \end{bmatrix} \end{aligned} \quad (14)$$

As a result, the *d*- and *q*-axis currents in the synchronous reference frame can be obtained by:

$$i_{ds}^e = I_m(-\frac{\alpha}{2}\sin 2\theta_e) \quad (15)$$

$$i_{qs}^e = I_m + \alpha I_m(\frac{1+\cos 2\theta_e}{2}) \quad (16)$$

If the *d*-axis currents in (13) and (15) equal each other, the error component of the *d*-axis current can be represented as:

$$\sin\theta_{err} = -\frac{\alpha}{2}\sin 2\theta_e \quad (17)$$

In (17), when θ_{err} is small, the position error can be derived by:

$$\theta_{err} \approx -\frac{\alpha}{2}\sin 2\theta_e \quad (18)$$

In addition, the ripple frequency of the electrical rotor position in relation to the number of resolver and motor poles can be expressed as:

$$\theta = \frac{P_{resolver}}{P} \times \theta_e \quad (19)$$

where, $P_{resolver}$ is the number of resolver poles and P is the number of motor poles.

The torque equation of the PMSM becomes [7]:

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_f i_{qs}^e \quad (20)$$

where, λ_f is the rotor flux linkage due to the rotor permanent magnet.

The torque ripple due to position error can be obtained by substituting (16) into (20):

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_f I_m(1+\alpha\frac{1+\cos 2\theta_e}{2}) \quad (21)$$

From (15), (16) and (21), the torque and *dq*-axes currents of the PMSM have ripples caused by the position error of the resolver signals.

4. Proposed Compensation Algorithm

The position error caused by the amplitude imbalance has a periodic ripple as described in (10). The exact frequency component of this ripple is directly related to (19). Fig. 4 shows the ideal rotor position and the real position including the position error. The position error causes periodic ripples in the *d*- and *q*-axis currents of the synchronous reference frame as described in (15) and (16). As shown in Figs. 4(a) and (b), the ideal rotor position θ_{ideal} increases linearly under normal velocity. However, the rotor position of the PMSM, including the position error $\theta_e + \theta_{err}$, can be distorted as shown in Figs. 4(a) and (b).

In (10), the amplitude imbalance of the resolver signals $\alpha/2$ can be easily detected by subtracting from **Area-0** to **Area-1** according to the rotor position [0, $\pi/2$], as shown in Fig. 4(c). As shown in Fig. 4(d), $\sin 2\theta_e$ with

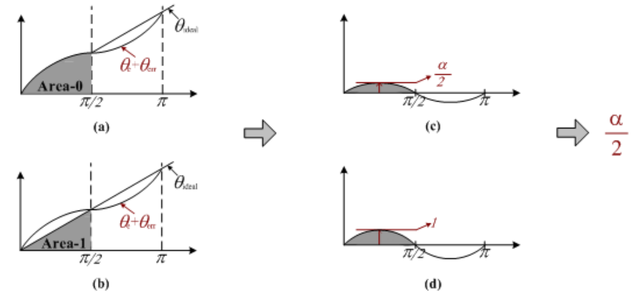

Fig. 4. Conceptual block diagram of the proposed algorithm.

amplitude=1 must be integrated from 0 to $\pi/2$ to obtain $\alpha/2$, and divided from Fig. 4(c).

Fig. 5 shows a block diagram of the proposed compensation algorithm for rotor position error. The periodic component $\sin 2\theta_e$ can be multiplied to obtain the rotor position error, as shown in Fig. 5. The actual rotor position can be estimated by subtracting the rotor position error from the measured rotor position value.

Fig. 6 shows a block diagram of the PMSM drive including the proposed compensation algorithm. As shown in Fig. 6, the rotor position, including the amplitude imbalance, can be directly compensated for by calculating the magnitude of the position error $\alpha/2$.

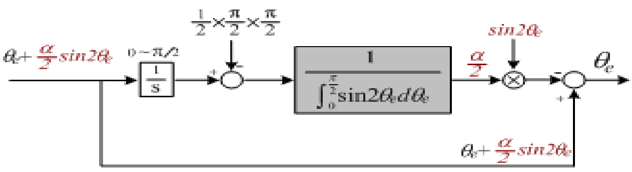

Fig. 5. Block diagram of the compensation algorithm of rotor position error.

5. Simulation Results

To show the effectiveness of the proposed algorithm, computer simulations were carried out using a PMSM drive with an R/D converter. The difference of the amplitude imbalance was added to the real position; then, α = 0.3 [%]. Fig. 7 shows a simulation diagram of the PMSM drive including the proposed compensation algorithm.

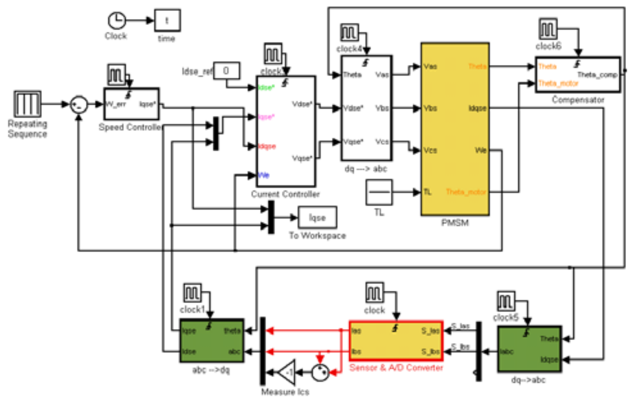

Fig. 7. Simulation diagram of the PMSM drive including the proposed compensation algorithm.

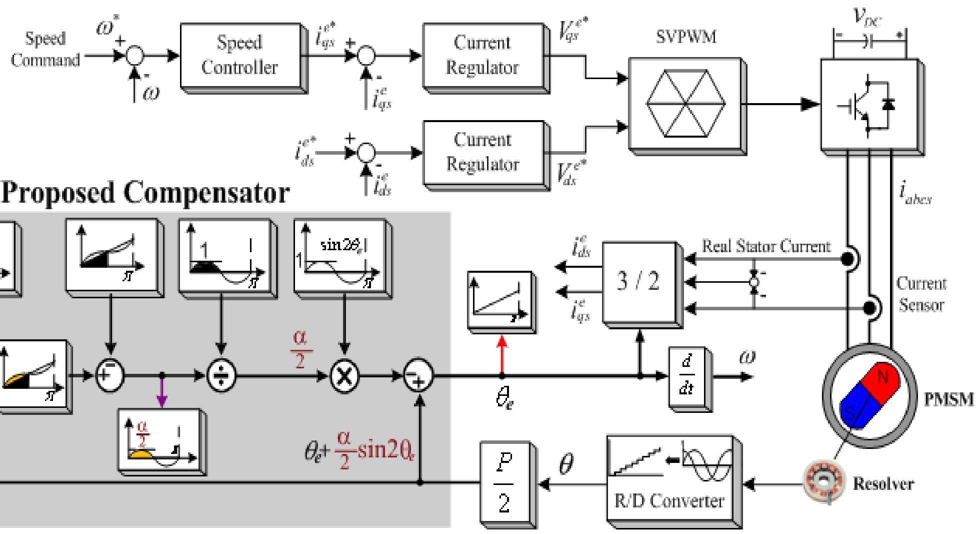

Fig. 6. Block diagram of the proposed compensation algorithm.

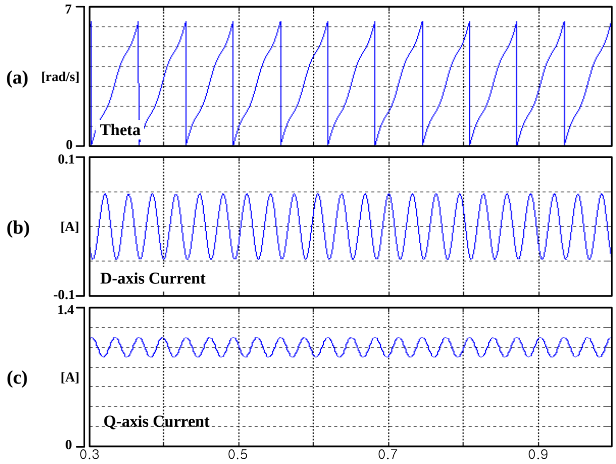

Fig. 8. Simulation results before compensation (200 r/min). (a) Rotor position. (b) *d*-axis current. (c) *q*-axis curr ent.

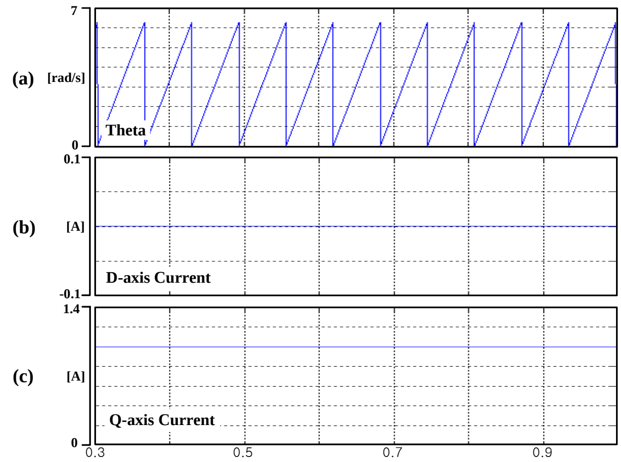

Fig. 9. Simulation results after compensation (200 r/min). (a) rotor position. (b) *d*-axis current. (c) *q*-axis current.

Fig. 8 shows the simulation results of the rotor position and *dq*-axes currents before the application of the proposed compensation algorithm when the motor was operating at 200 rpm. In Fig. 8, the rotor position has the twice the ripple component because of the amplitude imbalance of the resolver signals. As a result, the *d*- and *q*-axis currents of the synchronous reference frame include the harmonic component of the stator fundamental frequency.

However, after compensation, the rotor position is nearly linear, and the ripples of the *dq*-axes currents are significantly decreased, as shown in Fig. 9.

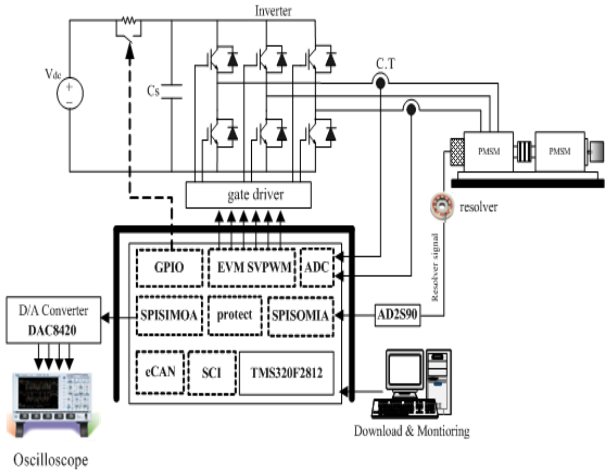

Fig. 10. Configuration of DSP-based control system for PMSM drive.

6. Experimental Results

The proposed method was implemented in a DSP-based control system of a PMSM drive system, as shown in Fig. 10. The specifications of the PMSM are 1.5 kW, 7.5 A, and 6-poles with 6-pole resolvers [8]. The processor is a fixed-point DSP (TMS320F2812). The sampling period and switching period for the drive system were set to 100 μs.

To verify the proposed compensation algorithm, the difference of the amplitude imbalance was given ($\alpha = 0.3$).

Figs. 11 and 12 show the experimental results of the rotor position, the *d*- and *q*-axis currents and the FFT results, with and without compensation, when the motor was operating at 200 rpm, respectively. Fig. 11 shows the distorted rotor position without compensation. As a result, the *dq*-axes currents have two times the ripple component and the rotor position is distorted, as shown in Fig. 11. Fig. 12 shows the improved rotor position and the *dq*-axes currents due to the proposed compensation algorithm. With the proposed algorithm, the ripple component of two times the stator fundamental frequency was significantly reduced, as shown in Fig. 12.

Figs. 13 and 14 show the experimental results at 1000 rpm. Without the compensation algorithm, the position error causes *dq*-axes current ripples of two times the stator fundamental frequency, as shown in Fig. 13. However, as

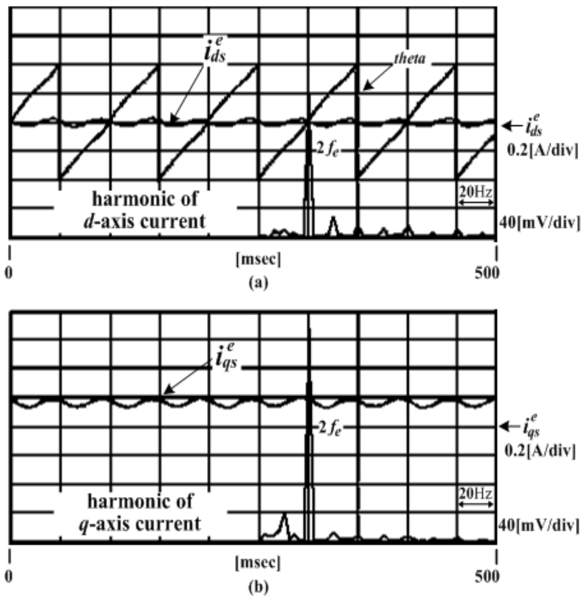

Fig. 11. Experimental results without compensation (200 r/min).
(a) rotor position, *d*-axis current, and FFT result.
(b) *q*-axis current and FFT result.

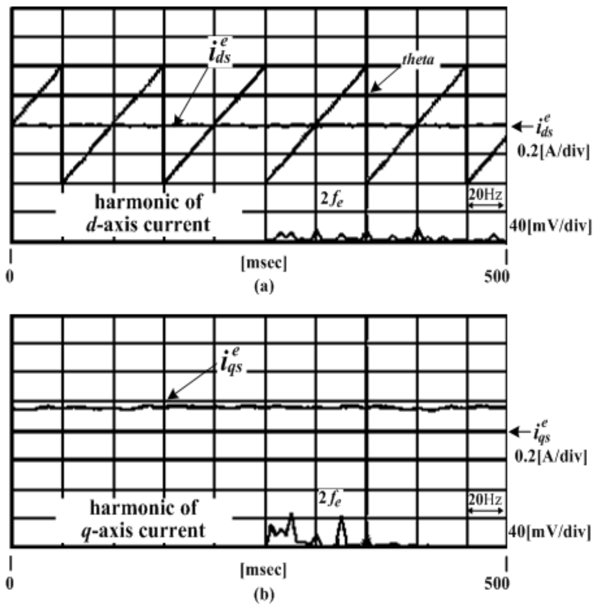

Fig. 12. Experimental results with compensation (200 r/min).
(a) rotor position, *d*-axis current, and FFT result.
(b) *q*-axis current and FFT result.

shown in Fig. 14, the ripple component of *d*- and *q*-axis decreased considerably with the proposed compensation algorithm.

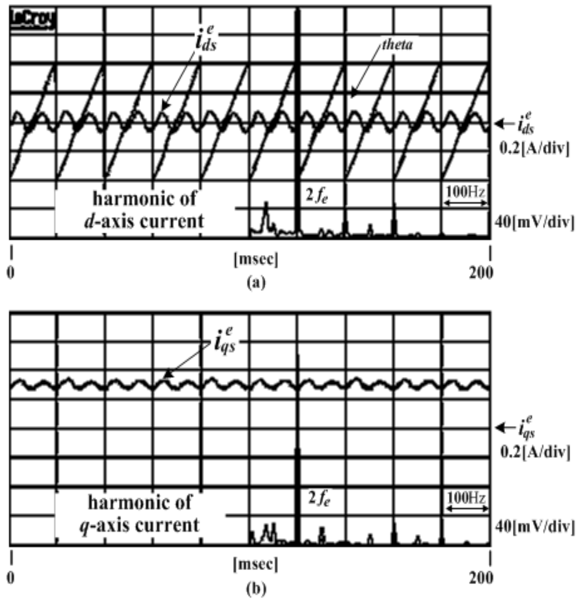

Fig. 13. Experimental results without compensation (1000 r/min).
(a) rotor position, *d*-axis current, and FFT result.
(b) *q*-axis current and FFT result.

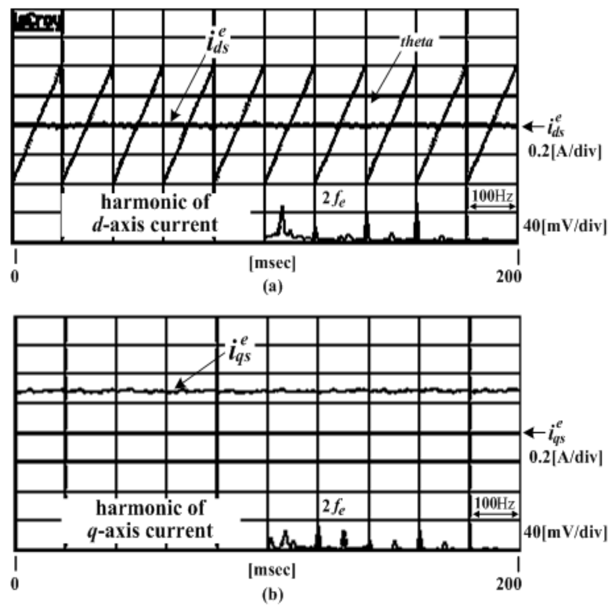

Fig. 14. Experimental results with compensation (1000 r/min).
(a) rotor position, *d*-axis current, and FFT result.
(b) *q*-axis current and FFT result.

7. Conclusions

In AC drive systems using resolvers, the *d*- and *q*-axis current ripples of two times the stator fundamental frequency are caused by an amplitude imbalance between resolver output signals such as differences in the transformer ratio, unbalanced excitation signal, and nonlinear characteristics in the signal process circuit. Due to these non-ideal characteristics, the control performance of AC motor drives is definitely degraded.

This paper proposes a new compensation algorithm for rotor position error by an amplitude imbalance of the resolver signals. The magnitude of the position error is detected by an integral operation in the position signal of an R/D converter to the specified rotor position. Therefore, it is easy to implement the proposed algorithm with a simple mathematic calculation using an integral operation without additional hardware. Moreover, the distorted rotor position is directly compensated for with only a few computational steps.

Simulation and experimental results show the effectiveness and feasibility of the proposed method.

Acknowledgment

This work was supported for two years by Pusan National University Research Grant.

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