Sensorless Initial Rotor Position Estimation of Surface Permanent-Magnet Synchronous Motor

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***Abstract*—This paper presents a method of estimating the initial rotor position of a surface permanent-magnet synchronous motor without a position sensor. The estimation is performed by using the nonlinear magnetization characteristics of the stator core caused by the magnet of the rotor. This method is based on the principle that the d-axis current value for the voltage vector applied to the motor under some conditions increases as the voltage vector generated from the inverter approaches the N pole of the rotor. During the estimation process, the rotor is practically at standstill. The experimental results show that the average of the estimation error is $\pm$3.8 electrical degrees.**

***Index Terms*—Magnetic saturation, sensorless initial rotor position estimation, surface permanent-magnet synchronous motor.**

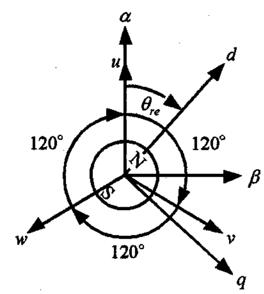

Fig. 1. Motor model.

I. Introduction

RECENTLY, permanent-magnet synchronous motors (PMSMs) have been used as high-performance variable-speed motors in many industrial applications because they have several inherent advantages, such as rugged construction, easy maintenance, high efficiency, and high power factor. PMSMs are generally constructed with a fixed rotor field supplied by rotor-mounted magnets.

Drives of PMSMs require the absolute rotor position information to exactly control the motor torque, and the position information has been provided by a resolver or an encoder. These sensors increase the machine size and the cost of the drive and, in addition, they reduce the reliability of the system. Therefore, many authors have published papers about position and speed sensorless drive methods of the PMSM [1]–[5]. For surface motors, there is a serious problem, in that it is quite difficult to estimate the rotor position at standstill. If the rotor position can not be exactly estimated, the starting torque of the motor decreases, and the large reversal rotation may be temporarily observed at starting [3]. Several methods to estimate the initial rotor position have been presented [5]–[7]. However, most of them are methods for interior-type PMSMs and are based on the principle that the inductance of interior-type motors is changed according to the rotor position.

In this paper, the initial rotor position estimation method of the surface PMSM without a position sensor is described. The initial rotor position is estimated based on the variation of current response caused by the magnetic saturation of the stator core. It is unnecessary to use the motor parameters for the estimation, and the rotor is practically at standstill during the operation of estimation. Experimental results show that the average of the estimation error is $\pm$3.8 electrical degrees in the test motor.

II. Initial Rotor Position Estimation

A. Motor Model

Fig. 1 shows the model of the surface PMSM. The orthogonal two-phase α–β frame is fixed to the stator windings. The d–q frame shows the synchronously rotating reference frame and the d axis coincides with the N pole of the rotor, and θ_{re} represents the actual angle of the rotor position.

B. Principle of Estimation

The estimation of the rotor position is based on the nonlinear magnetization characteristics of the stator core. The stator core close to a field magnetic pole is strongly magnetized. Therefore, if a stator winding is close to the magnetic pole of the rotor, the current in the stator winding flowing in the magnetizing direction is large compared with the absolute value of the stator current flowing in the demagnetizing direction because of the magnetic saturation of the stator core.

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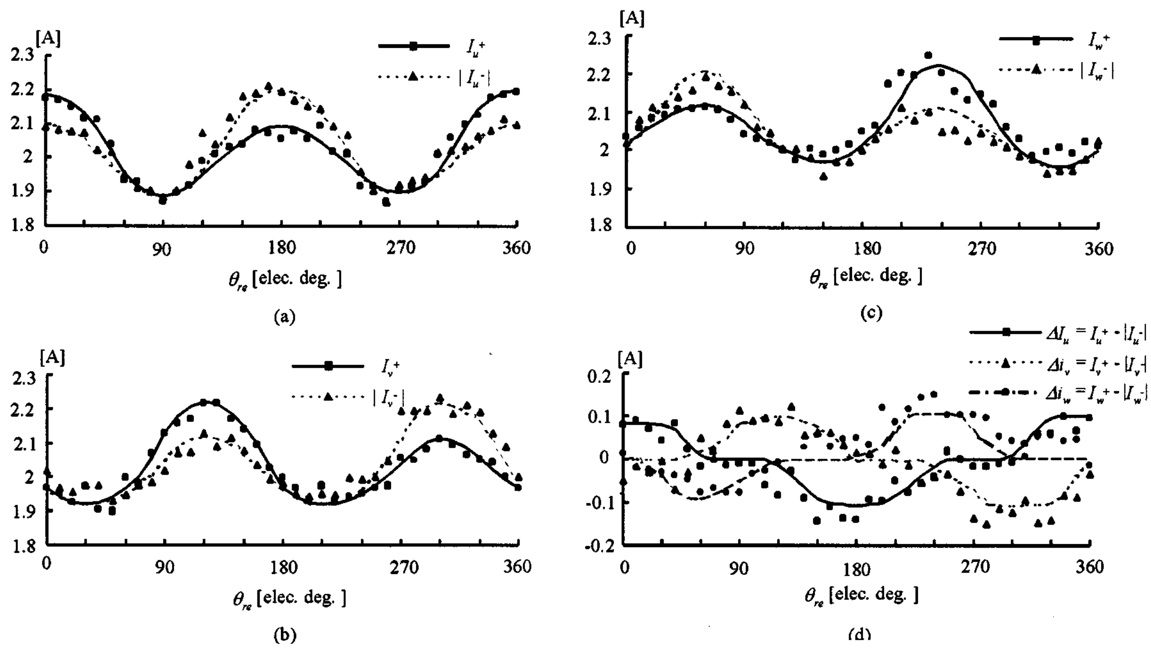

Fig. 2. Measured currents. (a) u-phase currents. (b) v-phase currents. (c) w-phase currents. (d) Difference between I^+ and $|I^-|$.

Fig. 2 shows the measured phase currents when the constant voltage vectors are applied to the stator winding of the test motor (see Section III-A). The current I_u^+ shown in Fig. 2(a) is the measured u-phase current for the angle of the rotor position when the voltage vector which coincides with the direction of the u-phase winding is applied to the motor, and I_u^- is also the measured u-phase current when the voltage vector is generated in the opposite direction of the u-phase winding. Fig. 2(b) and (c) is obtained from similar experiments. In this figure, the negative currents I^- are replaced by the absolute ones $|I^-|$ to easily compare with the positive currents I^+. Furthermore, the difference between I^+ and $|I^-|$ is shown in Fig. 2(d). As is obvious from Fig. 2, the difference between the positive and the negative currents is about 0.1 A around the points where the N pole coincides with the winding of each phase.

Consequently, the initial rotor position can be estimated using this phenomenon caused by the magnetic saturation.

C. Estimation Method

The estimation method is divided into two processes in this study. The flow chart of the estimation is shown in Fig. 3. In the estimation, the voltage vector is provided in the direction of the *voltage_angle* shown in Fig. 3. The number n is the one of the voltage vector shown in Fig. 4 and θ_n is the angle of the voltage vector n.

In the first process, 12 distinct voltage vectors are provided to the motor in numerical order ($1 \rightarrow 2 \rightarrow 3 \rightarrow \cdots \rightarrow 12$) as shown in Fig. 4, and the d-axis current transformed from the three-phase currents is measured. Every time the voltage vector is provided for 200 μs, all gate signals of the inverter are turned off during 600 μs to force each phase current zero. The rotor position is estimated using these d-axis current values in this method. When the voltage vector n is applied to the motor, if the d-axis current I_d is larger than the maximum d-axis current $I_{d\_\max}$ that is initially set to zero, I_d is the new maximum d-axis current $I_{d\_\max}$ and the *voltage_angle* is the estimated angle θ_{M1}. As the voltage vector approaches the N pole, the d-axis current gradually increases because of the magnetic saturation. Finally, the maximum d-axis current can be obtained and the angle of the N-pole position θ_{M1} can be estimated as the angle of the voltage vector where the maximum d-axis current is observed. The estimation error must be smaller than ± 15 electrical degrees, as is obvious from Fig. 4.

In the second process, first, θ_{M1} is replaced by θ_{M2}, and three kinds of the voltage vectors whose angles are $\theta_{M2} - \Delta\, angle$, θ_{M2}, and $\theta_{M2} + \Delta\, angle$ are provided to the motor based on the result of the first process. The initial value of $\Delta\, angle$ is 7.5 electrical degrees, therefore, these voltage vectors are applied in the direction of $\theta_{M2} - 7.5$, θ_{M2}, and $\theta_{M2} + 7.5$ electrical degrees, as shown in Fig. 5. The voltage vector 14 equals the vector giving $I_{d\_\max}$ in the first process. The new estimated angle θ'_{M2} of the N-pole position can be obtained by the same way as the first process for these voltage vectors. Accordingly, the accuracy of the estimated angle is ± 3.75 electrical degrees in this stage.

Next, the voltage vectors 16, 17, and 18 are applied to the motor as shown in Fig. 6, and the new estimated angle θ''_{M2} can be similarly obtained. Furthermore, the voltage vectors 19, 20, and 21 are applied to estimate the more accurate angle, as shown in Fig. 7.

Consequently, the angle of the provided voltage vector that shows the maximum d-axis current equals the final estimated angle.

Since the position of the magnetic pole is estimated by using the current response for the voltage vector provided from the

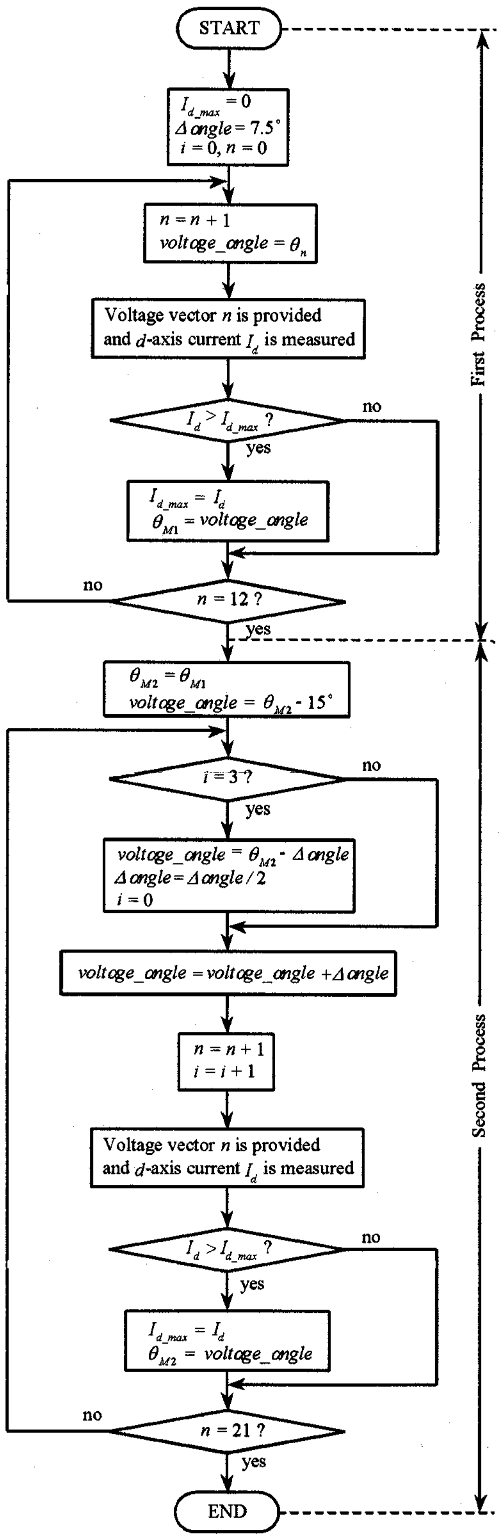

Fig. 3. Flowchart.

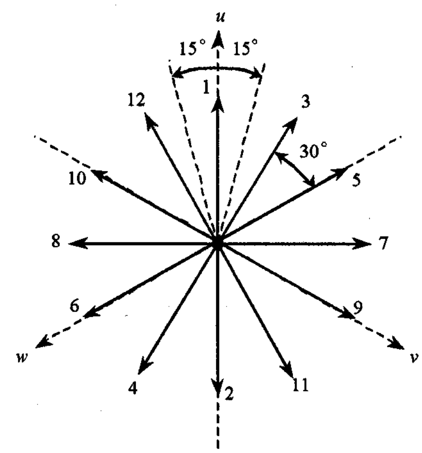

Fig. 4. Voltage vectors used in the first process.

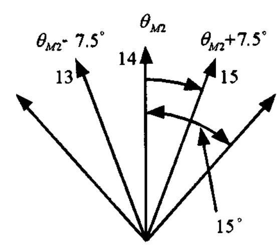

Fig. 5. Voltage vectors.

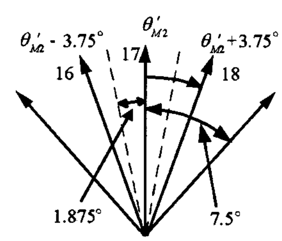

Fig. 6. Voltage vectors.

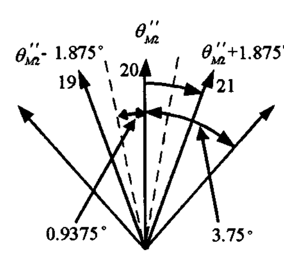

Fig. 7. Voltage vectors.

inverter, this method is not affected by the set errors and the variation of the motor parameters. The theoretical maximum accuracy of the rotor position angle estimated by this method is ±0.9375 electrical degrees.

D. Decision of Amplitude and Output Time of Voltage Vectors

The amplitude and the output time of the voltage vector are important because the estimation is implemented based on the current response when the voltage vector is applied. The amplitude of the voltage vector is defined by multiplying the dc

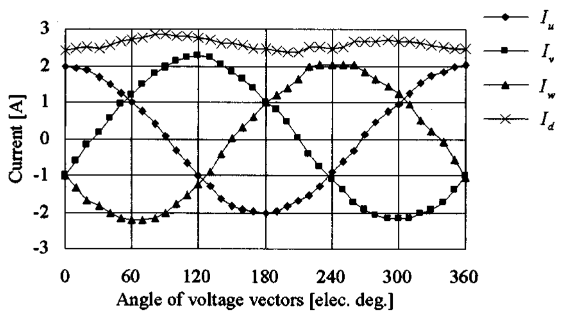

Fig. 8. Measured currents.

source voltage E_d of the inverter and the modulation factor. The voltage vector must be determined so as to be able to observe the difference between I^+ and $|I^-|$ and to implement the estimation without rotating the rotor. Table I shows some measured u-phase currents when the voltage vectors 1 and 2 shown in Fig. 4 are provided to the motor. During the measurement, the actual rotor position angle θ_{re} is set to 0 electrical degrees. In this table, m is the modulation factor and T_s is the output time of the voltage vector. The modulation factor and the output time that meet the conditions mentioned above can be obtained by this experiment, and m is 0.57 and T_s is 200 ms. In this case, the difference between I_u^+ and $|I_u^-|$ is about 0.1 A, and this value is enough quantity for this estimation. Fig. 8 shows each phase current and the d-axis current measured for various voltage vectors under $m = 0.57$ and $T_s = 200$ μs when θ_{re} is 90 electrical degrees. As shown in this figure, the d-axis current has two peaks around the points where the angles of the voltage vectors are 90 and 270 electrical degrees, and the difference between these peaks is about 0.15 A.

Although the motor generally moves when a voltage vector is provided to the motor for the estimation, it does not move when the appropriate voltage vector with the optimal modulation factor and the output time is used. A method for automatically determining this voltage vector is under development at present. However, the rotor axis can align with an axis determined by a specified gate pattern given to the inverter [8], and then the appropriate voltage vector can be determined by trial and error. Since the estimation is implemented using this voltage vector in this study, the rotor does not move during the operation of estimation. When the voltage vector except this one is used, the rotor must be locked by a mechanical brake.

III. Experimental Results

A. System Configuration

The experimental system for laboratory test is illustrated in Fig. 9. The test motor is a 400-W 1.9-A four-pole surface PMSM. A high-performance digital signal processor (DSP) (TMS320C32) controller is used to implement the proposed estimation algorithm. The stator currents of the motor are detected with LEM modules (CT5-T), and are transformed into the digital signals through a 12-bit A/D converter. The actual rotor position is detected with a rotary encoder (RE) mounted on its shaft for monitoring, and the resolution of the RE is 4000 counts per revolution. DC source voltage E_d is 282 V.

B. Position Estimation Results

In this experiment, for an example, the actual rotor position angle θ_{re} is set to 0 electrical degrees. Fig. 10(a) shows the d-axis current I_d and the maximum d-axis current $I_{d\_\max 1}$ measured according to the first process mentioned previously. As is obvious from Fig. 10(a), the estimated angle θ_{M1} is 0 electrical degrees.

Next, according to the second process, the voltage vectors are provided to the motor in numerical order (13→14 →15). In this case, each voltage vector in the direction of -7.5, 0, and 7.5 electrical degrees is provided to the motor. As shown in Fig. 10(b), the new maximum d-axis current $I_{d\_\max 2}$ is obtained when the voltage vector 14 nearest to the N pole of the rotor is provided. Therefore, the new estimated angle θ'_{M2} equals θ_{M2} (0 electrical degrees) in this case. Furthermore, the voltage vectors 16, 17, and 18 are provided, and $I'_{d\_\max 2}$ can be obtained for the voltage vector 17. After all, θ''_{M2} equals θ'_{M2}. This process is repeated once more for the voltage vectors 19, 20, and 21. Obviously, from Fig. 10(b), the final estimated angle is also 0 electrical degrees.

Figs. 11 and 12 also show the experimental results when θ_{re} is set to 279 and 90 electrical degrees, respectively. As is obvious from Figs. 11(a) and 4, θ_{M1} is 270 electrical degrees. In the second process, $I_{d\_\max 2}$ is obtained when the voltage vector 15 is provided, and θ'_{M2} is 277.5 electrical degrees. When the voltage vectors 16, 17, and 18 are provided, the rotor position angle should be between $\theta'_{M2} - 1.875$ and $\theta'_{M2} + 1.875$ electrical degrees because $I'_{d\_\max 2} < I_{d\_\max 2}$, as shown in Fig. 11(b). Therefore, the voltage vectors 19, 20, and 21 are provided in the direction of $\theta'_{M2} - 1.875$, θ'_{M2}, and $\theta'_{M2} + 1.875$ electrical degrees, and $I''_{d\_\max 2}$ is obtained for the voltage vector 20. The final estimated angle is 277.5 electrical degrees and the estimation error is 1.5 electrical degrees.

In Fig. 12(a), since $I_{d\_\max 1}$ is obtained for the voltage vector 7, the estimated angle of the first process θ_{M1} is 90 electrical degrees. According to the second process, the final estimated angle is 88.125 electrical degrees, and the estimation error is 1.875 electrical degrees in this case.

Fig. 13 shows the estimated rotor position compared with the actual rotor position. The estimation was performed at 4.5-electrical-degree intervals from 0 to 360 electrical degrees. As a result, the average of the estimation error was ± 3.8 electrical degrees, and the maximum estimation error was 18.75 electrical degrees. The maximum error is observed near the only one point where θ_{re} is 180 electrical degrees. The measured each phase current and d-axis current are shown in Fig. 14, when θ_{re} is fixed at 180 electrical degrees. Although the d-axis current must be maximum at 180 electrical degrees by the magnetic saturation, the d-axis current at 180 electrical degrees is less than that at 150 and 210 electrical degrees. Therefore, the estimation failed in the first process at $\theta_{re} = 180$ electrical degrees, and the final estimation error is serious. This phenomenon was not observed at every other rotor position. Therefore, it is

TABLE I
MEASURED U-PHASE CURRENTS

T_s [μs]	m	I_u^+ [A]	$\lvert I_u^- \rvert$ [A]	$I_u^+ - \lvert I_u^- \rvert$	T_s [μs]	m	I_u^+ [A]	$\lvert I_u^- \rvert$ [A]	$I_u^+ - \lvert I_u^- \rvert$
100	1	4	2.95	1.05	200	1	4.05	3.68	0.37
	0.9	1.8	1.75	0.05		0.9	3.62	3.33	0.29
	0.8	1.65	1.55	0.1		0.8	3.15	2.92	0.23
	0.7	1.39	1.33	0.06		0.7	2.71	2.55	0.16
	0.6	1.18	1.12	0.06		0.6	2.26	2.14	0.12
	0.5	0.94	0.9	0.04		0.5	1.88	1.81	0.07
	0.4	0.74	0.71	0.03		0.4	1.44	1.4	0.04
	0.3	0.51	0.51	0		0.3	1.11	1.05	0.06
	0.2	0.32	0.32	0		0.2	0.67	0.64	0.03
	0.1	0.11	0.06	0.05		0.1	0.33	0.32	0.01

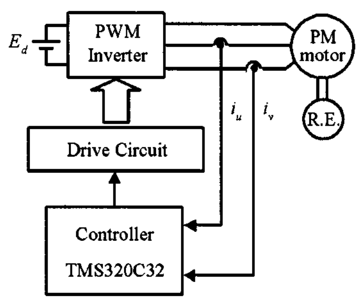

Fig. 9. Experimental system.

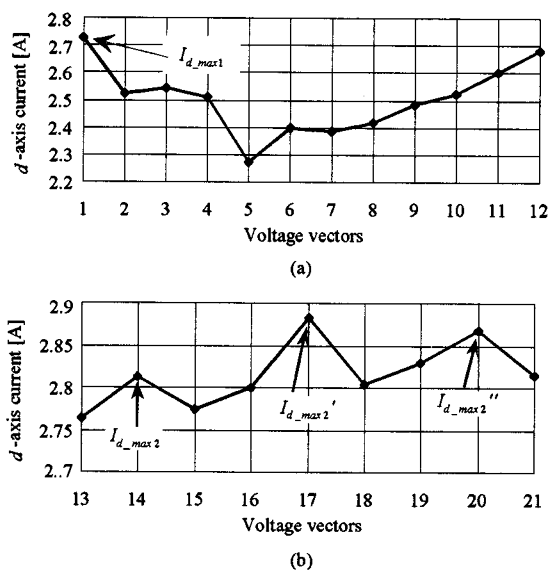

Fig. 10. Estimation result when the actual angle is 0 electrical degrees. (a) d-axis current in the first process. (b) d-axis current in the second process.

considered that this is caused by the inherent rotor structure of the test motor and is a special case.

IV. CONCLUSION

A new initial rotor position estimation method of surface PMSM without a position sensor has been proposed. This method is performed based on the d-axis current response for

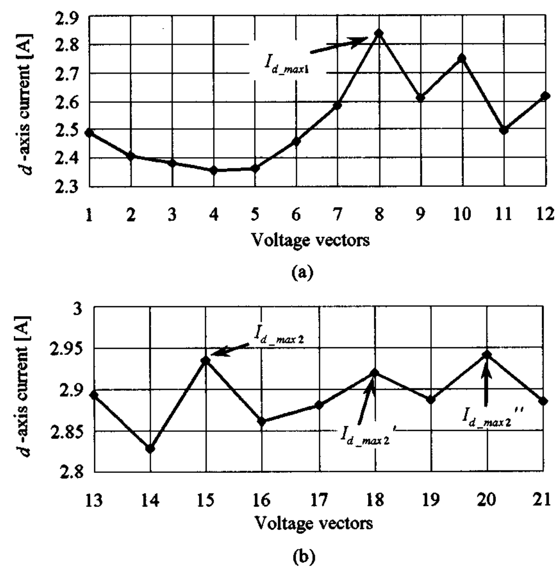

Fig. 11. Estimation result when the actual angle is 279 electrical degrees. (a) d-axis current in the first process. (b) d-axis current in the second process.

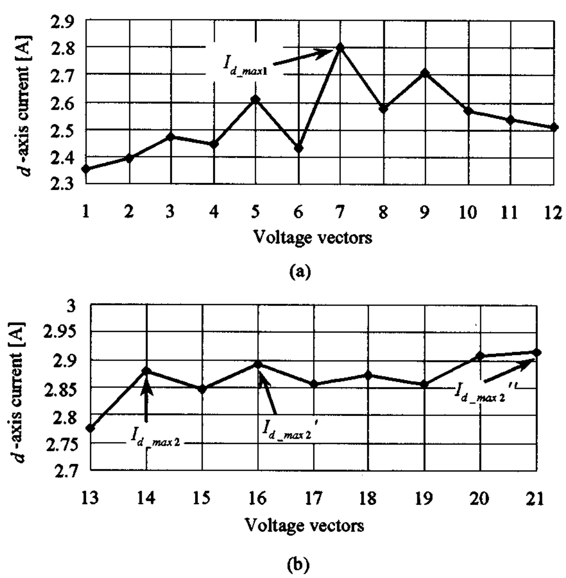

Fig. 12. Estimation result when the actual angle is 90 electrical degrees. (a) d-axis current in the first process. (b) d-axis current in the second process.

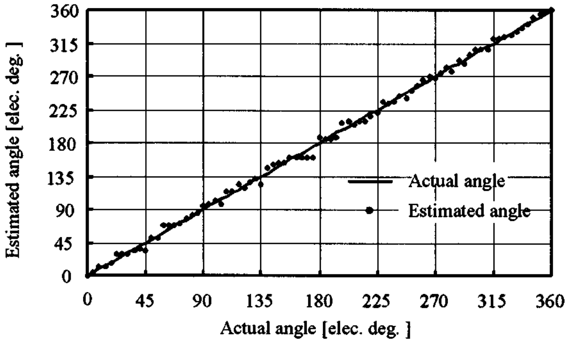

Fig. 13. Estimation results.

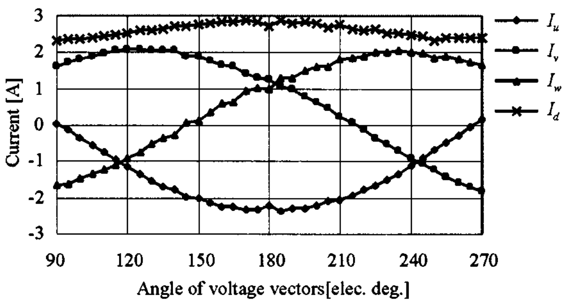

Fig. 14. Measured currents.

the voltage vector applied to the motor, and uses the magnetic saturation of the stator core. During the estimation process, the rotor is practically at standstill, and the estimation is completed within about 17 ms. According to experimental results, the average of the estimation error is ± 3.8 electrical degrees, and the maximum estimation error is 18.75 electrical degrees. Other features of the proposed estimation method are no requirement of additional hardware and robustness to the set errors and the variation of the motor parameters.

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