Evaluation Method to Estimate Position Control Error in Position Sensorless Control Based on Pattern Matching Method

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A sensorless control based on a pattern matching method is proposed for interior permanent magnet synchronous motors which have non-sinusoidal inductance spatial distribution, at a standstill and in very-low-speed regions. A previous study indicated that closed-loop-position sensorless control can be achieved under heavy load conditions. However, position control errors are generated at atypical rotor positions, and the reason for this has not been clarified. Moreover, there remains an issue in which this position error cannot be perceived before position sensorless control is carried out.

This study examines why position control errors are generated in the pattern matching method. Furthermore, an evaluation method that estimates position control error in advance is proposed using the clarified mechanism of position error generation. The effectiveness of the proposed method is demonstrated by comparing experimental and evaluation results.

Keywords: interior permanent magnet synchronous motor, position sensorless control, pattern matching, position control error, evaluation method, magnetic saturation

1. Introduction

Owing to the growth of power electronics technology and the development of permanent magnets, Interior Permanent Magnet Synchronous Motors (IPMSMs) are widely utilized in many applications such as home appliances, industrial equipment, and automobiles because of their compact size, high efficiency, and excellent control response. In order to accurately control IPMSMs, the information of the rotor position is necessary. However, using a position sensor such as an optical encoder has disadvantages such as high cost and installation space requirements. Thus, a position sensorless control that estimates the rotor position without using a position sensor has attracted attention.

Many sensorless techniques for IPMSMs have been proposed\textsuperscript{(1)-(8)}. In medium and high-speed regions, a commonly used method is based on the extended electromotive force (EEMF), which is generated proportional to the rotor speed\textsuperscript{(1)-(3)}. At a standstill and in very-low-speed regions, a method using the angle dependency of the inductance spatial distribution is generally utilized\textsuperscript{(3)-(7)}. In Refs. (3)-(7), methods were proposed that inject a signal into the estimated coordinate and derive the estimated position from the amplitude of the response current. In addition, a method using both an observer of the EEMF and signal injection was proposed in Ref. (8).

Almost all these position sensorless control methods assume that the phase inductance spatial distribution is sinusoidal. However, in recent years, there are an increasing number of cases where the assumption does not hold. For example, in traction motor drive systems such as Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs), there is a tendency to positively utilize the magnetic saturation region to satisfy the strict demands of high power density and high torque density. In previous studies\textsuperscript{(9)-(10)}, it was reported that IPMSMs driving in the magnetic saturation region have non-sinusoidal spatial distribution, and it is difficult to apply a general position sensorless control method.

To achieve the position sensorless control for IPMSMs that are non-sinusoidal, a pattern matching method has been proposed. The proposed pattern matching method estimates the rotor position by matching the feature values measured in real time with the values in a template that is prepared beforehand. In Ref. (10), it was demonstrated that a closed-loop-position sensorless control is possible under heavy load conditions by experimental results.

In principle, this position estimation method is heavily dependent on phase inductance spatial distributions of a target IPMSM. In fact, even in the Ref. (10), a strange position control error occurred in the results, and the cause of the error was not fully studied. Hence, even if the inductance spatial distribution can be given in advance, the position control error cannot be perceived until actual experiments are performed.

Based on this background, this paper reports on the cause of position control errors that occurred during closed-loop-position sensorless control based on a pattern matching.
method. Furthermore, an estimation method of position control error by pattern matching method is proposed from phase inductance spatial distribution of target IPMSM without actually performing any experiments.

A summary of position sensorless control based on a pattern matching method, and the issues involved, are described in section 2. In section 3, the causes of position control errors are explained. These errors occurred when closed-loop-position sensorless control was carried out. In section 4, a method to estimate position control error from phase inductance spatial distribution of target IPMSM. In section 5, the effectiveness of the proposed method is validated through matching the experimental and evaluation results, and section 6 brings this paper to a conclusion.

2. Pattern Matching Method

2.1 Target IPMSM Having Non-sinusoidal Inductance Spatial Distribution

Table 1 lists the parameters of the IPMSM used in this paper for position sensorless control based on a pattern matching method. The target IPMSM was designed to have a power density equal to that of an automobile, and to reach magnetic saturation easily. Figure 1 shows the measured \(\phi\) phase inductance spatial distribution for rotor positions in various load current conditions. As shown in Fig. 1, distortion occurs in the phase inductance even though the load current is zero. Furthermore, the inductance becomes more intricate when the load current is increased. A previous study\(^{(10)}\) indicated that the control is unstable when using a conventional method based on the characteristic for which the inductance spatial distribution is sinusoidal. In addition, the study reported that position sensorless control becomes possible by using the proposed pattern matching method under the same conditions.

2.2 Pattern Matching Method

An overview of the pattern matching method is shown in Fig. 2. The procedure of the method is as follows. First, template data sets are created beforehand by measuring feature values that vary depending on the rotor position at every position. Then, while position sensorless control is carried out, observation data is measured in the same way as when the template data is created. Finally, the rotor position is estimated by searching for the most similar angle between the template data and observation data by using pattern matching.

In the previous study, the current derivatives were utilized as feature values because the current derivatives are inversely proportional to the phase inductance, which changes depending on the rotor position, as represented by (1). where \(L_x\) is the \(x\) phase inductance, \(V_{dc}\) is the DC-link voltage, and \(pi\) is a \(x\) phase current derivative (\(x \in u, v, w\)).

\[
L_x \propto \frac{V_{dc}}{|pi|} \quad \text{..................................(1)}
\]

If the DC-link voltage is the same, the current derivatives can be used for feature values instead of phase inductance by fixing the voltage vector at which the current derivatives are measured. In the previous study, by injecting high-frequency signals of \(\pm V_{hsv}\) for the \(u\) phase and \(\mp V_{hsw}\) for the \(v\) and \(w\) phases at every half carrier period, \(V1(1,0,0)\) and \(V4(0,1,1)\) voltage vectors are created intentionally, and the current derivatives are measured at the voltage vector. As an example, Fig. 3 shows the switching command, output voltages of the inverter, current behavior after signal injection, and measurement timing for \(u\) phase current, in a zero-load condition. By measuring the current derivatives for \(v\) and \(w\) phase currents in the same way, six feature values can be obtained during every carrier period. Then, the Sum of Squared Difference (SSD) is utilized as an evaluation function for pattern matching, and the rotor position is estimated.

2.3 Issues of Previous Method

Figure 4 shows the experimental results of the closed-loop-position sensorless control under each load current condition. By using the pattern matching method, a closed-loop-position sensorless control becomes possible in every load condition, even with the target IPMSM having a non-sinusoidal phase inductance spatial distribution. However, strange position control errors occur under all conditions except for the zero-load condition. This is because the method does not utilize a mathematical

![Fig. 1. Phase inductance spatial distributions of target IPMSM](image1)

![Fig. 2. Overview of pattern matching method](image2)
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3. Analysis of Position Control Error

3.1 Relationship between Current Phase Angle and Feature Value

Although we examined changing the accuracy of template data and the bandwidth of the LPF in order to improve the strange position control error, it was verified that position estimation errors occur that cannot be explained by using the measurement accuracy of feature values. As a reason for the error, we investigated the possibility that the error occurs by referring to the template data of different currents (due to the position error).

Figure 5 shows the coordinate system used in this paper. αβ-axis is the stator-oriented coordinates, dq-axis is the rotor-oriented coordinates, and γδ-axis is the estimated coordinates. \( \theta_r \) is a real rotor position, \( \hat{\theta}_r \) is an estimated rotor position, \( \Delta \theta_r \) is a position estimation error, and \( \phi_i \) is a current phase angle in the dq-coordinate system. It is assumed that if an axis error occurs when the closed-loop control is performed, feature values vary by observing the current on the γδ-axis. In addition, it is assumed that if pattern matching is performed using feature values different from template data sets created on the dq-axis, a position estimation error is generated.

In order to investigate the relationship between the current phase angle and the feature value, the feature values were measured while changing the current phase angle from \(-20^\circ\) to \(20^\circ\) in \(5^\circ\) increments under a 75% rated current load condition. Figure 6 and Fig. 7 show the feature values of u phase current measured at the V1 and V4 voltage vectors. From the measurement results, it can be verified that the feature values change depending on the current phase angle, the influence of magnetic saturation is different depending on the
rotor position, and the change is nonlinear. For example, in
the vicinity of 130° of Fig. 6, if the current phase angle devi-
ates by 5°, the feature value changes by about 0.5%. By con-
trast, the current phase angle is hardly affected in the vicinity
of 270°. Furthermore, for the v and w phase current changes,
measurement results for which the feature values vary non-
linearly depending on the current phase angle (such as in the
u phase) were obtained.

Owing to these results, it is expected that if an axis error
occurs, the feature values change as the current phase angle
changes, and that it affects the estimated rotor position. In ad-
dition, since the relationship between the current phase angle
and the feature value is nonlinear, it is difficult to calculate
the estimated rotor position by analysis (such as modeling
the change of the feature value).

3.2 Calculation of Estimated Position by Evaluation
Function

In this section, the estimated position is exam-
ined when pattern matching is performed using feature values
different from the template data. As described previously, if
an axis error Δθre occurs, the current phase angle φi is varied
by an amount corresponding to the error. Owing to this re-
relationship between the axis error and current phase angle,
if a feature value table of all current phase angles is prepared,
the rotor position can be estimated by calculating the eval-
uation function while changing the current phase angle that
Corresponds to the position error.

The evaluation function utilized for pattern matching is
represented as (2).

\[
J(\theta_t, \theta_{re}, \phi_i) = \sum_{n=1,4,4} \left( p_{x,Vn}(\theta_t) - p_{x,Vn}(\theta_{re}, \phi_i) \right)^2 \]  

Where \( p_{x,Vn}(\theta_t) \) is the template data of x phase current mea-
sured at the Vn voltage vector, \( p_{x,Vn}(\theta_{re}, \phi_i) \) is a value from
the feature value table when the rotor position is at \( \theta_{re} \),
and the current phase angle is \( \phi_i \). Furthermore, the estimated
position can be determined so that a value of the evaluation
function is minimized and is represented as (3).

\[
\hat{\theta}_{re} = \arg \min_{\theta_t, \theta_{re}, \phi_i} J(\theta_t, \theta_{re}, \phi_i) \]  

To explain the mechanism by which a position error occurs
by the deviation of the current phase angle, the u phase tem-
plate data and values from the feature value table of each cur-
et phase angle when the rotor position is 140° are shown in
Fig. 8 as an example. Figures 8(a) and (b) are the results
measured at the V1 and V4 voltage vectors while varying the
current phase angle from −20° to 20° in 5° increments. From
these results, it can be verified that even the rotor position is
same, there are feature values which are likely to occur an
obvious difference from the template data, and feature values
with little difference to template data also exists at the same
time. Hence, the rotor position can only be estimated by cal-
culating the evaluation function with all six feature values.

Figure 9(a) shows the calculation result of the evaluation
function of each current phase angle, and Fig. 9(b) shows the
result of enlarging around the real rotor position. The rotor
position where the value of the evaluation function is at the
minimum is represented by a circle, and the position is the
estimated position of each current phase angle. When the
real rotor position is 140° and the position error occurs in the
rotation direction of the IPMSM (\( \Delta \theta_{re} > 0° \)), the estimated
position tends to converge to 132°. On the other hand, when

In this section, we introduce an evaluation method to estimate the position control error that occurs during position sensorless control. The procedure of the proposed evaluation method is shown below.

(1) Creating the template data sets ($\phi_i = 0^\circ$)
(2) Creating the feature value table of variable current phase angle
(3) Calculating the estimated rotor position using evaluation function
   (3.1) Determining the real rotor position $\theta_{re}$ and current phase angle $\phi_i$ ($\phi_i = -\Delta \theta_{re}$)
   (3.2) Calculating the evaluation function $J(\theta, \theta_{re}, \phi_i)$ (Eq. (2))
   (3.3) Calculating the estimated rotor position (Eq. (3))
   (3.4) Calculating the position error ($\Delta \theta_{re} = \theta_{re} - \hat{\theta}_{re}$)

If the template data sets and feature value table of all current phase angles can be prepared in advance, the estimated position error can be calculated by repeating the calculation from (3.1) to (3.4) until the estimated position converges.

Figure 11 shows a flowchart of the proposed evaluation method.

5. Comparison of Proposed Evaluation Method and Experimental Results

5.1 Experimental Setup
In order to indicate the validity of the proposed evaluation method, evaluation and experimental results are compared. Figure 12 shows the configuration of the control system. The target IPMSM is operated at 0.1% rated speed by a load machine. The rotor position is estimated by a position estimator based on the pattern matching method, and the estimated rotor position is used for $dq$-transformation. Table 2 lists the parameters and experimental setup for measuring the feature values. The V1
and V4 voltage vectors for which the feature values are measured are generated by signal injection. The amplitude of the injection signal was set to 33.3% of the DC-link voltage, and the current sampling time interval was set to 45 [μs] to obtain the current derivative. The angular resolution of the template data was set to 1 [deg]. In addition, the general PI control system with a bandwidth of 1000 [rad/s] is consistent. The bandwidth of the LPF was set to 500 [rad/s] to avoid unnecessary switching noise.

5.2 Setup of Evaluation

The evaluation is performed as shown in Fig. 11, and the parameters used in the evaluation are listed in Table 3. The used feature value tables for the current phase angle are prepared by measuring the feature value while changing the phase angle of the current command during the experiment instead of during the magnetic field analysis. To estimate the position control error more accurately, the angular resolution of the feature value table is set to 1° in the vicinity of the current phase angle of the current command, and the resolution is set to 5° for other current phase angles. In addition, the initial position error is set to 0°, and the position error is generated by the rotation of the rotor. However, for a position error to occur, the rotor position (θre) was rounded up, and the estimated position (θ̂re) was rounded down. This is because the angular resolution of the prepared table (1°) is very large as compared with the rotation angle of the motor during one period of evaluation (0.075°).

5.3 Results of Experiment and Evaluation

The experimental and evaluation results from 25% to 100% with 25% intervals of rated current are shown in Fig. 13–Fig. 16. The average estimated position error and the maximum error of the proposed evaluation method are almost the same as those in the experimental results. In addition, the rotor positions at which strange position errors occur also are the same. From the vicinity of 140° and 320° in Fig. 14, it can be...
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verified that a position error rarely occurs in the direction of the rotor rotation since the position error is returned. These results demonstrate that the proposed evaluation method can estimate the position control error beforehand if a feature value table of all current phase angles is prepared.

6. Conclusion

In this paper, an evaluation method to estimate the position control errors that occur during closed-loop-position sensorless control based on a pattern matching method is proposed. Using the pattern matching method, closed-loop-position sensorless control under heavy load conditions for an IPMSM with non-sinusoidal inductance spatial distribution is possible. However, a position control error can occur, and it is difficult to perceive the error before position sensorless control is performed.

This paper indicated that the current phase angle changes by observing the current in the estimated coordinate axis including the axis error, and that feature values different from the template data sets are measured. In addition, position estimation errors occurred as a result of pattern matching using different feature values with template data sets. Furthermore, a novel method was proposed that evaluates the position control error in advance if the inductance spatial distribution is provided. In order to perform the proposed evaluation method, it is necessary to prepare feature value tables of every current phase angle. Simultaneously, it is necessary to select feature values from the table according to the position errors, and to perform pattern matching using the evaluation function. The validity of the proposed evaluation method was indicated because the evaluation results for various load conditions coincided with the experimental results.

In this paper, the effectiveness of position sensorless control based on pattern matching method and the proposed evaluation method was demonstrated with one target IPMSM. The pattern matching method is expected to applicable with other IPMSMs, if the feature values depend on the rotor position and if the feature values having reproducibility can be measured. In addition, if the cause of the position control error is only that the feature values change as the current phase angle changes, the proposed evaluation method may also be effective when applying pattern matching method to other IPMSMs. It is necessary to confirm the effectiveness of proposed method with multiple IPMSMs, in the future.

In this evaluation, the feature value table of the current phase angle through experiments is utilized, but it is necessary to confirm whether the evaluation is possible using the feature value table prepared by magnetic field analysis. Moreover, although the mechanism by which the position error occurs is clarified, a method to improve upon the error has not yet been studied. These are future works.

References


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