Position Sensorless Control of IPMSMs using Full-Order Flux Observer Based on an Algebraic Design Method

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In this paper, a position sensorless control method for IPMSMs using a full-order observer based on an algebraic design is proposed. The full-order observer is well known to be one of the powerful estimators for sensorless control of AC motors, for which design strategies have already been discussed. Although many numerical design and heuristic design approaches have been proposed so far, the design formulation for improving robustness with respect to mismatches in some parameters, however, is now an open problem. First, the proposed flux model for position sensorless control of IPMSMs has been reviewed, in which this model can approximately estimate the maximum torque control (MTC) frame, which stands for a new coordinate aligned with the current vector at the MTPA control. Next, an algebraic design of the full-order observer based on the proposed flux model has been proposed. In this paper, a design guideline to suppress the sensitivity of the speed estimation error has also been proposed. Finally, some experimental results demonstrate the effectiveness of the proposed method.

Keywords: IPMSM, Position Sensorless Control, Full-Order Observer, Algebraic Design, Maximum Torque Per Ampere Control, Flux Model

1. Introduction

Interior permanent magnet synchronous motors (IPMSMs) are widely applied in various fields, such as household appliance, industry field, and so on, because IPMSMs realize high efficiency and contribute to system compactness. To the IPMSMs for high efficiency control, detection of the rotor position is necessary. However, position sensors for detection of this signal decrease reliability and restrict the environment for installation. Therefore, position sensorless control has been required, and various strategies have been proposed so far (1)–(4).

The maximum torque per ampere (MTPA) control, which optimizes the overall torque including the reluctance torque, is often utilized as the most efficient drive of IPMSMs. In order to implement this control, generally, accurate parameters are required (5)–(6). Inductances dramatically vary, however, due to magnetic saturation, which has been one of the most important problems in recent years.

On the other hand, the maximum torque control (MTC) frame, which stands for a new coordinate aligned with the current vector at the MTPA control, has been proposed (7)–(8), in which the MTC frame is directly estimated based on the modified extended electromotive force (EEMF), and the position sensorless control technique on this frame is realized. In addition, this approach is reinterpreted by other researchers (9)–(10). We have also proposed a similar technique based on the new flux model (11).

However, in these literatures, the transient characteristics of the MTC frame estimation approach has not been discussed enough, and therefore we have discussed these characteristics in the case of our proposed flux model. As a result, in the MTC frame estimation methods, it has been confirmed that rapid load changes cause a transient speed estimation error. Therefore, in these methods, it is considered that the robustness of the speed estimation error is necessary. From the above discussion, this study employs the full-order observer because it is well known to be one of the robust estimators for sensorless control of AC motors (12)–(17).

The position sensorless control method using the full-order observer, which originates from the literature (12), has also been applied to IPMSMs. In the case of sensorless control with the full-order observer, even though the importance of the observer gain design has been pointed out (13)–(17), the optimal pole assignment method seems to be an unsolved problem.

The literature (13) has already proposed the observer gain design method based on Riccati equation. This demonstrates that the stable position sensorless control in a whole region of drive without zero speed is possible. Although this approach can maintain the stability of the observer, however, the results of pole assignment is not illustrated clearly which implies that the estimation error convergence performance is not known. In addition, a numerical design method has some problem, such as a design method is complicated and some numerical analysis software may also be required. Therefore, the observer gain design using algebraic calculation is important for the general-purpose improvement and cost reduction.

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Position Sensorless Control of IPMSMs  

Atsushi Matsumoto et al.

On the other hand, in the literature (12), an algebraic design method of observer gain has already been proposed. It is known however this method destabilizes in the near of rated speed (13)(14). Furthermore, in the literature (14), by reinterpretation of the literature (12), the observer gain design method which ensures stability in the near of rated speed has been proposed. In this literature, the filter characteristics of observer have also been discussed. As a results, the stable position sensorless control in the near of rated speed region becomes possible. The error convergence performance however is not illustrated clearly. To the contrary, in the literature (16), the observer gain design method based on the 2-stage design has been proposed. This method has clarified the error convergence performance. On the other hand, in the literature (17), the observer gain design guideline which is determined by the stability condition of observer has been proposed. It has partly clarified that the physical meanings of the observer gain from structure of the observer.

It should be noted, however, these approaches have not discussed for robustness of position sensorless control, especially to suppress the influences of the speed estimation error. In position sensorless control, the speed estimation error is unfortunately inevitable, which is often caused by acceleration and deceleration and by other parameter mismatches. The speed estimation error degrades performance in position sensorless control and would also cause instability. Therefore, improving robustness for the speed estimation error is one of the most important problems for stable position sensorless control.

In this paper, a position sensorless control method for IPMSMs using the full-order observer based on an algebraic design has been proposed. First, the proposed flux model for position sensorless control of IPMSMs has been reviewed where this model can approximately estimate the MTC frame (11). In addition, in the MTC frame estimation method, it has been shown that load changes cause the transient speed estimation error. Next, an algebraic design of full-order observer based on the proposed flux model has been proposed. In this paper, a design guideline to suppress the sensitivity of the speed estimation error to the phase estimation error has also been proposed. Finally, some experimental results demonstrate the effectiveness of the proposed method.

2. MTPA-Oriented Flux Model for Position Sensorless Control of IPMSMs

2.1 Derivation of Flux Model (11) First, a novel mathematical model for position sensorless control of IPMSMs is derived. The voltage equation of IPMSMs on the rotating coordinate ($d-q$ axis) is given by

\[
\begin{bmatrix}
\nu_d \\
\nu_q \\
\end{bmatrix} = \begin{bmatrix}
R + pL_d & -\omega_r L_q \\
\omega_r L_d & R + pL_q \\
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q \\
\end{bmatrix} + \begin{bmatrix}
0 \\
\omega_r K_e \\
\end{bmatrix},
\]

(1)

where

\[
\begin{align*}
\nu_d, \nu_q & \text{ voltage on } d-q \text{ axis;} \\
i_d, i_q & \text{ current on } d-q \text{ axis;} \\
R & \text{ resistance;} \\
L_d & \text{ inductance of } d \text{ axis;} \\
L_q & \text{ inductance of } q \text{ axis;} \\
p & \text{ differential operator;}
\end{align*}
\]

The speed estimation error degrades performance in position sensorless control and would also cause instability. Therefore, improving robustness for the speed estimation error is one of the most important problems for stable position sensorless control.

In this paper, a position sensorless control method for IPMSMs using the full-order observer based on an algebraic design has been proposed. First, the proposed flux model for position sensorless control of IPMSMs has been reviewed where this model can approximately estimate the MTC frame (11). In addition, in the MTC frame estimation method, it has been shown that load changes cause the transient speed estimation error. Next, an algebraic design of full-order observer based on the proposed flux model has been proposed. In this paper, a design guideline to suppress the sensitivity of the speed estimation error to the phase estimation error has also been proposed. Finally, some experimental results demonstrate the effectiveness of the proposed method.

This subsection
clarifies that the phase relationships between the proposed flux and the current for torque maximization.

The phase relationships between $d-q$ axis and the proposed flux ($\gamma-\delta$) axis are shown in Fig. 2, where $\delta$, $\gamma$, and $\Delta\theta$ stand for $\delta$-axis and the MTPA current phases from with $d$-axis, $q$-axis and the MTPA axis respectively. $\theta$ stands for $\delta$-axis phase from with $\alpha$-axis, and is given by

$$\theta = \tan^{-1}\left(\frac{L_q}{L_d}\right)$$

Generally, the current phase $\theta_i$ under the MTPA control is expressed as the follow:

$$\theta_i = \tan^{-1}\left(-\lambda_d + \frac{\lambda_q^2}{2L_q}\right)$$

$$= \tan^{-1}\left(-\frac{2L_q}{\tan\gamma} \right)$$

On the other hand, from (3), $\theta_i$ is given by

$$\theta_i = \tan^{-1}\left(\frac{L_q}{L_d}\right) = \tan^{-1}\left(\frac{(L_q - L_d)\lambda_q}{L_E}\right)$$

It should be noted that the MTC frame can be estimated by the proposed flux coordinate if $\theta_i = \theta$, yielding the MTPA control can be realized by the regulating current amplitude on the proposed flux coordinate.

Figure 3 shows that $\Delta\theta$ characteristics between the proposed flux and the current for torque maximization with increase of $(L_q - L_d)\lambda_q/K_E$. From this figure, $(L_q - L_d)\lambda_q/K_E$ of less than 0.556 gives rise to five degrees or less in $\Delta\theta$.

The test IPMSM with parameters listed in Table 1 satisfies relation of $(L_q - L_d)\lambda_q/K_E = 0.556$ at the rated current. Therefore, the proposed flux estimation makes it possible to estimate the MTC frame, which enables to eliminate the MTPA control algorithm with some parameters.

### 2.3 Transient Characteristics of $L_q$ model and its Influences on Speed Estimation

In the literatures (7) and (8), the position sensorless control methods based on the MTC frame have first been proposed. Then, the literatures (9) and (10) have refined this approach from the individual point of view, however, in these literatures, the transient characteristics of the estimated phase which involves with load changes have not been discussed.

Therefore, in this paper, the transient characteristics of the MTC frame estimation have been discussed based on $L_d$ model. As a result, in the MTC frame estimation methods, it is found that load changes cause the transient speed estimation error. This subsection clarifies that the MTC frame estimation methods would give rise to the transient speed estimation error.

The phase relationships between $d-q$ axis and $\gamma-\delta$ axis in a steady state are shown in Fig. 4. Figure 4(a) shows the phase relationships at no load, and therefore $\gamma-\delta$ axis is aligned with $d-q$ axes. Figure 4(b) shows the phase relationships at load, and $\gamma-\delta$ axis advances from $d-q$ axis. Here, this paper discusses the transient characteristics under

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**Table 1. Parameters of test IPMSM**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>1600 min$^{-1}$</td>
</tr>
<tr>
<td>Rated Current</td>
<td>5.0 A</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>200 V</td>
</tr>
<tr>
<td>$R$</td>
<td>0.55Ω</td>
</tr>
<tr>
<td>$L_d$</td>
<td>8.31 mH</td>
</tr>
<tr>
<td>$L_q$</td>
<td>22.35 mH</td>
</tr>
<tr>
<td>$K_E$</td>
<td>2.006 V·s/rad</td>
</tr>
<tr>
<td>Pole Pairs</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Fig. 4. Physical relationships of coordinates in steady state**

(a) at no load (b) at load
load changes. If the load torque is applied to a motor, the estimation coordinate \( (\gamma - \delta \text{ axis}) \) moves from \( d - q \text{ axis} \) as shown in Fig. 4 because \( \lambda_p \), which is expressed by (3), is increased with load increasing. In the moment, \( \gamma - \delta \) axis has the transiently faster angular speed than \( d - q \text{ axis} \) because the angular speed of \( \gamma - \delta \) axis is accelerated with the moving of coordinate. Also, \( \gamma - \delta \) axis has the transiently lower angular speed than \( d - q \) axis for the similar reason if the load torque is transitioned from applied load to no load. Figure 5 shows that the load step responses using the MTC frame estimation method, where

- \( i_\delta \) current on \( \delta \text{ axis} \);
- \( \omega_{m} \) mechanical rotation speed;
- \( \omega \) reference value;
- \( \hat{\omega} \) estimated value.

Figure 6 show the control system, where \( \alpha_1 \) and \( \alpha_2 \) are poles of the full-order observer which will be described in the following section. The experimental setup consists of an IPMSM with concentrated windings coupled with an induction motor for load regulation. It should be noted that the load step responses using the MTC frame estimation coordinate \( \theta \) is transitioned from applied load to no load. Figure 5 shows that the load step responses using the MTC frame estimation method, where

\[
i_\delta = 0,
\]

\[
\omega_m \text{ current on } \delta \text{ axis};
\]

\[
\omega_m \text{ mechanical rotation speed;}
\]

\[
\omega \text{ reference value;}
\]

\[
\hat{\omega} \text{ estimated value.}
\]

3. Proposed an Algebraic Design of Full-Order Observer

3.1 Construction of Full-Order Flux Observer Using Complex Vector Notation From \( L_d \) model of (4), IPMSMs can be described by a linear state equation as

\[
p[\begin{bmatrix} i \\ \lambda \end{bmatrix}] = \begin{bmatrix} -\frac{R}{L} I - \frac{\omega_m J}{L} & \frac{1}{L} I \\ \omega_m & \frac{1}{L} \end{bmatrix} \begin{bmatrix} i \\ \lambda \end{bmatrix} + \begin{bmatrix} \frac{1}{L} I \\ 0 \end{bmatrix} v + \begin{bmatrix} 0 \\
\end{bmatrix} W \label{eq:8}
\]

\[
i = C_1 \begin{bmatrix} i \\ \lambda \end{bmatrix} \label{eq:9}
\]

\[
\lambda = C_2 \begin{bmatrix} i \\ \lambda \end{bmatrix} \label{eq:10}
\]

where

\[
i = \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}^T
\]

\[
\lambda = \begin{bmatrix} \lambda_\alpha \\ \lambda_\beta \end{bmatrix}^T
\]

\[
v = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}^T
\]

\[
I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

\[
J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}
\]

\[
O = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}
\]

\[
C_1 = \begin{bmatrix} I \\ O \end{bmatrix}
\]

\[
C_2 = \begin{bmatrix} O \\ I \end{bmatrix}
\]

\[
W = p[\lambda] \begin{bmatrix} -\frac{1}{L} \cos \theta_{re} \\ -\frac{1}{L} \sin \theta_{re} \end{bmatrix}
\]

assuming that the electrical system’s time constant is smaller enough than the mechanical one, the speed \( \omega_{re} \) is regarded as a constant parameter. In this paper, the \( p[\lambda] \) term in \( W \), which makes it difficult to solve using the state equation, is neglected as unmodeled factor. In the above condition, IPMSMs can be expressed as linear combination of both the unit matrix and the skew-symmetric matrix because IPMSM can be regarded as SPM or as shown in (4). The full-order observer for SPMs have already been discussed according to the literature (12), the structure of the observer gain is restricted to a linear combination of the unit matrix and the skew-symmetric matrix, in this paper. Therefore, the full-order observer for IPMSM can be constructed on \( \alpha - \beta \) coordinate by

\[
p[\begin{bmatrix} i \\ \lambda \end{bmatrix}] = \begin{bmatrix} -\frac{R}{L} I - \frac{\omega_m J}{L} & \frac{1}{L} I \\ \omega_m & \frac{1}{L} \end{bmatrix} \begin{bmatrix} i \\ \lambda \end{bmatrix} + \begin{bmatrix} \frac{1}{L} I \\ 0 \end{bmatrix} v
\]

\[
+ h_{11} I + h_{12} J (\hat{i} - i), \label{eq:11}
\]

where \( h_{11}, h_{12}, h_{21} \) and \( h_{22} \) are the observer gains. It can be seen that (11) is complicated for designing these observer gains because this observer is constructed as the four-dimensional system.

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**Fig. 5.** Load step responses using the MTC frame estimation method \((\alpha_1 = \alpha_2 = -200)\)

**Fig. 6.** Control system (without the auto speed regulator)
Observer

This paper transforms the observer gain design into the pole assignment problem without a lack of general-
\[ \|G(j\omega)\|_{\infty} \leq \sup_{\omega} \frac{\omega + \alpha_1 \alpha_2 / \hat{\omega}_{re}}{\sqrt{\omega^2 + (\alpha_1^2 + \alpha_2^2)\omega^2 + (\alpha_1 \alpha_2)^2}}. \]

Although depending on the speed, it can be seen from (22) that the \( \|G(j\omega)\|_{\infty} \) is not reduced enough and it is difficult to suppress \( \Delta \lambda - \lambda \) due to \( \Delta \omega_{re} \) even if \( \alpha_1 \) and \( \alpha_2 \) are simultaneously designed to be high or low. On the contrary, the reduction of \( \|G(j\omega)\|_{\infty} \) can be realized when the one of poles is reassigned at high and the another is reassigned at low. Therefore, in this paper, \( \alpha_1 \) and \( \alpha_2 \) are designed as
\[ \alpha_2 \ll \alpha_1 < 0. \] (23)

The reason of this pole design guideline is in order to increase \( \alpha_1^2 + \alpha_2^2 \) which only included in the denominator and to decrease \( \alpha_1 \alpha_2 \) which included in the numerator and the denominator. As a result, this pole assignment makes it possible to achieve the robust flux estimation with respect to \( \Delta \omega_{re} \). It should be noted that \( \alpha_1 \) and \( \alpha_2 \) cannot be designed completely; thus, only the pole assignment guideline is obtained from the result of (23). Therefore, it is desirable that the one pole should be assigned near the origin and the another should be as far as possible.

### 3.3.3 Numerical Example

The gain characteristics of \( G(j\omega) \) in different pole assignments are shown in Fig. 8. The values of poles are shown in this figure. The rotor speeds are \( \hat{\omega}_{re} = 200 \text{ rad/s} \) (\( \hat{\omega}_{rm} = 955 \text{ min}^{-1} \)) and \( \hat{\omega}_{re} = 600 \text{ rad/s} \) (\( \hat{\omega}_{rm} = 2865 \text{ min}^{-1} \)). It should be noted that the relative value of the gain of \( G(j\omega) \) has significant meaning for robustness, because \( G(j\omega) \) is not sensitivity function of the position sensorless control system. It can be seen from these figures that the proposed design achieves the robust flux estimation with respect to \( \Delta \omega_{re} \) because \( G(j\omega) \) can be effectively suppressed in the vicinity of the rotor speeds. Figure 8 shows that although gain tends to increase at the low speeds.

In addition, experiments based on the proposed guideline were carried out. Figure 9 shows the load step responses using the MTC frame estimation method based on the proposed guideline. This experiment has same condition in Fig. 5 except for poles assignment. It turns out from this figure that the proposed guideline can be suppressed the fluctuation of the estimated speed. As a result, \( \lambda \) in Fig. 9 has shorter settling time than Fig. 5 one.

From the above, the proposed guideline realizes the robust flux estimation with respect to the speed estimation error.

### 4. Experimental Results

#### 4.1 System Setup

Experiments were carried out to show the effectiveness of the MTC frame estimation and the proposed guideline to suppress influence of the speed estimation error on flux estimation. Figure 10 shows the experimental setup. Experiment results in subsection 4.2, IPMSM was operated without the auto speed regulator as shown in Fig. 6. Experiment results in sub-sections 4.3 and 4.4, IPMSM was operated with the auto speed regulator as shown in Fig. 11. The parameters of test IPMSM are shown in Table 1. In following experiments, the proposed flux is estimated by the full-order observer as shown in...
Fig. 7. The estimated speed $\hat{\omega}_{re}$ is substituted with differential operation of $\hat{\theta}$ and through the first order low-pass filter (1000 rad/s). The full-order observer, the speed controller, the current controller, and the coordinate transformer were executed with DSP (TI:TMS320C6713B), and the pulse width modulation of the voltage reference was made by FPGA (Altera:EPF10K20TC144-4). The estimation period and the control period were 100 $\mu$s. Hence, the carrier frequency of the PWM inverter was 10 kHz. Also, the inverter output voltage through the second order low-pass filter (2 kHz), and the current were detected by 12 bit ADC. Rotor position and the torque for just verification were measured by FPGA and the torque meter (Magtrol:TMB306/411).

4.2 MTC Frame Estimation Results In following experiments, IPMSM was operated by position sensorless vector control with the proposed method. Figure 12 shows the MTC frame estimation results at 1800 min$^{-1}$, in which $\hat{\theta}_2$ stands for the estimated MTC current phase by using $L_d$ model. In these figures, solid lines represent the developed torque measurement results under constant current amplitude $|i| = 4.33$ A (50% of the rated current, $L_q \simeq 27$ mH) and 8.66 A (the rated current, $L_q \simeq 22$ mH), respectively. It turns out from Fig. 12 that errors of $\hat{\theta}_2$ are approximately suppressed to $4^\circ$ regardless current amplitude $|i|$, so that reduction of developed torque is hardly visible. Therefore, these experimental results conclude that $L_d$ model realizes the robust MTC frame estimation to magnetic saturation.

4.3 Flux Estimation Results In following experiments, IPMSM was operated by position sensorless vector control, and the observer is operated stand-alone. Figures 13 and 14 show the flux estimation results at 1000 min$^{-1}$ and 3000 min$^{-1}$ with no load, respectively. Poles were re-assigned as shown in these figures. Assignments of lower poles can achieve stable flux estimation at 1000 min$^{-1}$ as shown in Fig. 13(a), but cannot realize stable flux estimation at 3000 min$^{-1}$. Assignments of higher poles can achieve stable flux estimation at 1000 min$^{-1}$ and 3000 min$^{-1}$ as shown in Figs. 13(b) and 14(b), respectively, but harmonic component that is caused by concentrated windings is contained in the proposed flux as in Fig. 13(b). On the other hands, the proposed gain design makes it possible to realize robust flux estimation regardless the operating speed.

4.4 Load Step Responses In following experiments, IPMSM was operated by position sensorless vector control
using the full-order observer. Figures 15 and 16 show the load step responses at 1000 min$^{-1}$ and 3000 min$^{-1}$, respectively. Poles were reassigned as shown in these figures. These experimental results demonstrate the effectiveness of the proposed gain design for robust flux estimation with respect to the error or delay in speed estimation, caused by impact torque. Assignments of lower poles can achieve stable control at 1000 min$^{-1}$ as shown in Fig. 15(a), but cannot realize stable control at 3000 min$^{-1}$ even at no load (hence, not shown in Fig. 16). Assignments of higher poles cannot realize stable control at 1000 min$^{-1}$ as shown in Fig. 15(b), but can achieve stable control at 3000 min$^{-1}$ as shown in Fig. 16(b). Therefore, depending on the operating speed, higher poles cannot satisfy robust stability. On the other hands, the proposed gain design can achieve stable control at both 1000 min$^{-1}$ and 3000 min$^{-1}$. Hence, the proposed gain design makes it possible to realize robust position sensorless control with respect to the error in speed estimation regardless of the operating speed.

5. Conclusions

In this paper, the position sensorless control method for IPMSMs using full-order observer based on the algebraic design has been proposed. The conclusions of this paper are summarized as follows:

1. The proposed flux model for position sensorless control of IPMSMs has been reviewed. In addition, this paper has shown that can approximately estimate the MTC frame, and this model causes the transient speed estimation error under rapid load changes.

2. The algebraic design of full-order observer based on the proposed flux model has been proposed. Also, the design guideline of this observer to suppress the influences of the speed estimation error on the flux estimation has been proposed.

3. Some experimental results show the effectiveness of the proposed methods.

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