PARAMETER IDENTIFICATION OF PERMANENT-MAGNET SYNCHRONOUS MOTORS FOR SENSORLESS CONTROL

DRAGOȘ OVIDIU KISCK 1, JUNG HWAN CHANG 2, DO HYUN KANG 3, JI WON KIM 3, DRAGOȘ ANGHEL 1

Key words: Extended electromotive force (EEMF), Online parameter identification, Permanent-magnet synchronous motor (PMSM), Sensorless control.

An online parameter identification method is proposed for sensorless control for surface and interior permanent-magnet synchronous motors (SPMSMs and IPMSMs, respectively). As this method does not use rotor position or velocity to identify motor parameters, the identified parameters are not affected by position estimation error under sensorless control. The proposed method that is based on system identification theory can be applied to all kinds of synchronous motors. The effectiveness of the proposed method was verified by experiments in both SPMSMs and IPMSMs.

1. INTRODUCTION

There are mainly three kinds of synchronous motors, namely: surface permanent-magnet synchronous motors (SPMSMs), interior permanent-magnet synchronous motors (IPMSMs), and synchronous reluctance motors (SynRMs). Although rotor position and velocity can be used to achieve precise control of these motors, position sensors have several problems such as cost and durability. Therefore, many sensorless control methods have been proposed [1, 2].

These sensorless control methods can be mainly divided into two types, i.e., those using high-frequency voltage or current signals [3–14] and those using the fundamental components of voltage and current signals [3, 10]. The former methods use relations among three-phase currents [3], injection of high-frequency signals of voltages or currents [4–6, 10, 11], special inverter pulse width modulation (PWM) patterns [7], current response of step voltages [8, 9],

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information on harmonic reactive power [12], and a system identification method
to detect rotor position information, i.e., magnetic saturation or rotor saliency.
These methods are effective at standstill and in low-speed ranges because the
amplitude of high-frequency signals used for position estimation does not depend
on rotating velocity. Inasmuch as some methods do not need motor parameters to
estimate rotor position, position estimation error is not caused by parameter
variations. Early methods use detected terminal information on electromotive force
(EMF), information on phase of flux, difference of currents or voltages, and a
sliding observer for flux estimation to estimate rotor position information, i.e., back
EMF or rotor saliency. These methods are useful in middle and high-speed ranges
because they use the fundamental components of control signals for position
estimation and do not generate torque ripple or noises. However, these methods use
motor parameters to estimate rotor position, and position estimation error is caused
by parameter variations. In addition, the mathematical model of salient-pole
PMSMs is complicated, and position estimation using information of both back
EMF and saliency requires complicated calculations and approximation. An
extended EMF (EEMF) model, which is a mathematical model of synchronous
motors, has been proposed for position estimation in IPMSMs. Both of the EMF
generated by permanent-magnets and the EMF generated by rotor saliency are
included in the EEMF term, position estimation using the EEMF can be easily
realised for all kinds of synchronous motors. Sensorless control methods based on
EEMF require motor parameters to estimate rotor position just as other methods.
Because the motor parameters are changed by magnetic saturation and temperature,
a position estimation error is generated when there are differences between actual
motor parameters and ones used in the estimation system. Therefore, these
parameters should be measured in all driving areas, and a table of parameters
should be made to maintain accuracy. It is hoped that these parameters can be
measured online under sensorless control. In this paper, an online parameter
identification method for both SPMSMs and IPMSMs is proposed. The proposed
identification method does not use position and velocity to identify motor
parameters. With this method the parameter measurements are not necessary.

2. EEMF MODEL – CONSIDERATION IN PARAMETER VARIATIONS

2.1. THE COORDINATES AND SYMBOLS

Coordinates are defined in Fig. 1. The α–β frame is defined as the stationary
reference frame, the d–q frame is defined as the rotating reference frame, and the
γ–δ frame is defined as the estimated rotating reference frame. The symbols used in
this paper are presented in Table 1, Table 2 and the matrix definitions, in Table 3.
Table 1
Base quantities for [p.u.] system

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_h = \hat{U}_h$</td>
<td>rated voltage</td>
</tr>
<tr>
<td>$I_h = \hat{I}_h$</td>
<td>rated current</td>
</tr>
<tr>
<td>$\omega_h = \omega_h$</td>
<td>rated angular speed</td>
</tr>
<tr>
<td>$\Lambda_h = \hat{\Lambda}_h / \omega_h$</td>
<td>rated stator flux</td>
</tr>
<tr>
<td>$Z_h = \hat{V}_h / \hat{I}_h$</td>
<td>base impedance</td>
</tr>
</tbody>
</table>

Table 2
[p.u.] quantities

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_s = R_s / Z_h$</td>
<td>stator resistance</td>
</tr>
<tr>
<td>$l_d = x_d = L_d / L_h$</td>
<td>d-axis inductance</td>
</tr>
<tr>
<td>$l_q = x_q = L_q / L_h$</td>
<td>q-axis inductance</td>
</tr>
<tr>
<td>$[u_d, u_q]^T$</td>
<td>voltages on the rotating reference frame</td>
</tr>
<tr>
<td>$[\alpha, \beta]^T$</td>
<td>currents on the stationary reference frame</td>
</tr>
<tr>
<td>$[u_\alpha, u_\beta]^T$</td>
<td>voltages on the estimated rotating reference frame</td>
</tr>
<tr>
<td>$[l_\alpha, l_\beta]^T$</td>
<td>currents on the estimated rotating reference frame</td>
</tr>
<tr>
<td>$\lambda_{PM} = \Lambda_{PM} / \Lambda_h$</td>
<td>PM flux linkage</td>
</tr>
<tr>
<td>$\nu = \omega_{re} / \omega_h$</td>
<td>rotor speed</td>
</tr>
<tr>
<td>$\theta_{re} - \Delta \theta_{re}$</td>
<td>position estimation error</td>
</tr>
<tr>
<td>$p = d \cdot \nu / d t$</td>
<td>differential operator</td>
</tr>
<tr>
<td>$T_s$</td>
<td>sampling period of the identification system</td>
</tr>
</tbody>
</table>

Table 3
Matrix definitions

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I$</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>$J$</td>
<td>$\begin{bmatrix} 0 &amp; -1 \ 1 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>$O$</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>$Q(2\theta_{re})$</td>
<td>$\begin{bmatrix} \cos 2\theta_{re} &amp; \sin 2\theta_{re} \ \sin 2\theta_{re} &amp; -\cos 2\theta_{re} \end{bmatrix}$</td>
</tr>
<tr>
<td>$S(2\theta_{re})$</td>
<td>$\begin{bmatrix} -\sin 2\theta_{re} &amp; \cos 2\theta_{re} \ \cos 2\theta_{re} &amp; \sin 2\theta_{re} \end{bmatrix}$</td>
</tr>
</tbody>
</table>

2.2. THE EEMF MODEL

A mathematical model of synchronous motors on the rotating reference frame is written as (1); $I_d$ is equal to $I_q$ in SPMSMs.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} r_s + p l_d / \omega_n & -\nu l_q \\ \nu l_d & r_s + p l_q / \omega_n \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \nu \lambda_{PM} \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$ (1)
By transforming (1) in the stationary reference frame, (2) is derived.

\[
\begin{bmatrix}
    u_d \\
    u_q
\end{bmatrix} =
\begin{bmatrix}
r_s + pl_d / \omega_n & -vl_q \\
vl_q & r_s + pl_d / \omega_n
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} + \begin{bmatrix}
l_d \dot{i}_d \\
l_q \dot{i}_q
\end{bmatrix} + \begin{bmatrix}
0 \\
1
\end{bmatrix},
\]

(3)

where \( l_0 = (l_d + l_q) / 2 \) and \( l_1 = (l_d - l_q) / 2 \).

As shown in (2), there are two terms including position information \( \theta_{re} \). One is the back EMF term that includes \( \theta_{re} \) and is generated by a permanent-magnet, and the other is the \( Q(2\theta_{re}) \) term that includes \( 2\theta_{re} \) and is generated by rotor saliency. Because the position estimation using information on both terms is very complicated, conventional position estimation methods usually use just one of these terms, rotor saliency or back EMF. To solve this problem, an EEMF model is proposed as a mathematical model used in position estimation of synchronous motors. Equation (3) represents the EEMF model that is derived from (1) without approximation. Here, \( \dot{i} \) represents a differential of the \( q \)-axis current.

By transforming (3) to the one on the stationary reference frame, (4) is derived.
The third term on the right side of (4) is defined as EEMF and is shown in (5). The EEMF includes EMFs generated by both permanent-magnet and rotor saliency, and it is the only term in (4) that includes position information.

2.3. EFFECT OF PARAMETER VARIATIONS AND COUNTERMEASURES AGAINST IT

Differences between actual parameters and those used in position estimation, cause deterioration of position estimation accuracy under sensorless control. Because that is a serious problem for sensorless control using motor parameters, countermeasures against parameter variations are desired. In this paper, an online parameter identification method is proposed as a countermeasure. The objective of the parameter identification is to identify motor parameters used in position estimation to maintain accuracy. The proposed method has three advantages. Position and velocity are not used to identify motor parameters. Therefore, identified parameters are not affected by a position estimation error. Motor parameters can be identified online; thus, prior parameter measurements are not necessary. The proposed method can use any signal that satisfies the condition of persistent excitation, and special band-pass filters are not necessary.

3. PARAMETER IDENTIFICATION BASED ON SYSTEM IDENTIFICATION THEORY

3.1. PARAMETER MATRIX IDENTIFICATION USING A RECURSIVE LEAST-SQUARE METHOD

The proposed method identifies unknown motor parameters via a mathematical model using known values such as voltages and currents. The mathematical model is constructed on an estimated rotating reference frame because the model coefficients can be assumed to be almost constant regardless of the rotation conditions. By transforming (1) to the one on the estimated rotating reference frame, and by transforming the equation to a discrete equation, we have:

\[
\begin{bmatrix}
i_\alpha(k) \\
i_\beta(k)
\end{bmatrix} = \begin{bmatrix} [A] & [B] \\
[C] & [D]
\end{bmatrix} \begin{bmatrix}
i_\alpha(k-1) \\
i_\beta(k-1)
\end{bmatrix} + \begin{bmatrix} [E] \\
[F]
\end{bmatrix} [u](k-1) + \begin{bmatrix} [G] \\
[H]
\end{bmatrix} \begin{bmatrix}
\end{bmatrix} [I],
\]

(6)
Equation (6) is transformed as:

\[ y = \Theta \cdot z. \]  

(7)

\( \Theta \) is an unknown matrix and is defined as a parameter matrix that includes motor parameters. The vectors \( y \) and \( z \) are known vectors where:

\[ y = \begin{bmatrix} i_r(k) & i_s(k) \end{bmatrix}^T, \quad z = \begin{bmatrix} i_r(k-1) & i_s(k-1) & u_r(k-1) & u_s(k-1) & 1 \end{bmatrix}^T, \]

(8)

Using (7), the unknown parameter matrix \( \Theta \) is derived from known vectors \( y \) and \( z \) by using a least square method. This method identifies the parameter matrix \( \hat{\Theta} \) as the square value of the prediction error (9) reaches a minimum [13].

\[ e_i = \left( y - \hat{\Theta} \cdot z \right)^2. \]  

(9)

To identify the parameter matrix \( \Theta \) online, a recursive least-square method is used as shown in (10) and (11) [13]. The constant \( \lambda \) between 0 and 1 is defined as the weighting coefficient, the role of which is to delete past data. From:

\[ \hat{\Theta}(k) = \hat{\Theta}(k-1) + \left( y - \hat{\Theta}(k-1) \cdot z \right)^T \cdot P(k), \]  

(10)

\[ P(k) = \frac{1}{\lambda} \left( P(k-1) - P(k-1) \cdot z \cdot (\lambda + z^T P(k-1) z)^{-1} \cdot z^T P(k-1) \right), \]  

(11)

the parameter matrix \( \hat{\Theta} \) is identified recursively.

3.2. CHARACTERISTICS OF THE PARAMETER MATRIX

Because the position and velocity have to be estimated, the corresponding terms in the parameter matrix \( \Theta \) should be eliminated. The matrix \( \Theta \) consists of four matrices, namely: \( I, J, Q(2\Delta \theta_{re}), \) and \( S(2\Delta \theta_{re}). \) Here, \( I \) represents a unit
matrix, \( J \) represents a \( \pi/2 \)-radian rotation matrix, \( Q(2\Delta\theta_{re}) \) represents the matrix by which arbitrary points on a two-dimensional plane are moved symmetrically to the straight line of the \( \Delta\theta_{re} \) radian, and \( S(2\Delta\theta_{re}) \) represents the matrix that moves points symmetrically to the straight line of the \( \Delta\theta_{re} + \pi/4 \) radian. If the four matrices are represented as shown in (12), addition and subtraction of both diagonal and non-diagonal components of these matrices can be represented as shown in Table 4.

\[
X = \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{bmatrix}, \quad (X = I, J, Q(2\Delta\theta_{re}), S(2\Delta\theta_{re})).
\]  

(12)

<table>
<thead>
<tr>
<th>Characteristics of the matrices</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I )</td>
</tr>
<tr>
<td>( x_{11}^2 + x_{12}^2 )</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

3.3. PARAMETER DERIVATION FROM THE PARAMETER MATRIX

Using the relation in Table 4, motor parameters are derived without using position and velocity. The process of elimination of position/velocity terms is as:

\[
M_1 = b_{11} + b_{22} = \frac{2l_0}{l_d l_q} \omega_n T_s, \quad M_2 = a_{11} + a_{22} - 2 = -\frac{2r_j l_0}{l_d l_q} \omega_n T_s, \quad M_3 = \sqrt{(b_{11} - b_{22})^2 + (b_{12} + b_{21})^2} = -\frac{2l_0}{l_d l_q} \omega_n T_s. \quad (13)
\]

Using the variables \( M_1, M_2, \) and \( M_3 \), motor parameters are derived as:

\[
\hat{r}_i = -\frac{M_1}{M_2}, \quad \hat{l}_d = \frac{2\omega_n T_i}{M_1 + M_3}, \quad \hat{l}_q = \frac{2\omega_n T_i}{M_1 - M_3}. \quad (14)
\]

In this case, information on position and velocity is not used in (13) and (14); thus, the motor parameters can be derived independently of a position estimation error.

4. EXPERIMENTAL RESULTS

4.1. CONFIGURATION OF THE EXPERIMENTAL SYSTEM

Sensorless control with online parameter identification was realised using the same system in both an SPMSM and an IPMSM as Fig. 2 shows. The position
estimation, speed estimation and the observer from this figure are not discussed in this paper. Stator currents are detected by current sensors and are then sent to a floating-point digital signal processor (DSP TMS320C6713) through 16-bit analog-to-digital (A/D) converters. Three-phase current signals and voltage references are finally transformed into the estimated rotating reference frame.

From these current and voltage signals, motor parameters are identified in the proposed parameter identification system. These identified parameters pass through a low-pass filter, the decay time constant of which is set to 1.0 s for the inductance parameters and 10 s for the resistance parameter. The velocity controller is a polarization index (PI) controller; its outputs current references from the error between the estimated velocity and the velocity reference. The current control is done by two PI controllers for each axis and outputs voltage references from errors between reference current values and measured ones. Table 5 shows the specifications of both test motors, SPMSM and IPMSM.

**Table 5**

<table>
<thead>
<tr>
<th>Specifications of SPMSM and IPMSM</th>
</tr>
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<tbody>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Rated current</td>
</tr>
<tr>
<td>Rated speed</td>
</tr>
<tr>
<td>Number of pole pairs</td>
</tr>
<tr>
<td>Sampling period – ( T_s )</td>
</tr>
</tbody>
</table>
4.2. PARAMETER IDENTIFICATION RESULTS

Fig. 3 and Fig. 4 show the results of parameter identification for the SPMSM. Figure 3 shows results at no-load, whereas Fig. 4 shows results at rated load (9.5 Nm). $\hat{R}$ and $\hat{L}$ represent identified parameters. The reference velocity was set to 500 rot/min. From a comparison of Fig. 3 and Fig. 4, the identified parameters in both figures were approximately the same, and precise position estimation could be realised in both conditions. Fig. 5 and Fig. 6 show the results for the IPMSM. Fig. 5 shows results at no-load, and Fig. 6 shows results at rated load (9.5 Nm). $\hat{R}$, $\hat{L}_d$, and $\hat{L}_q$ represent identified parameters.

Comparing Fig. 5 and Fig. 6, we see that the identified parameters changed from 18 mH at no-load to 14 mH at rated load, and $\hat{R}$ changed from 0.3 $\Omega$ at no-load to 1.1 $\Omega$ at rated load. The change of $\hat{L}_q$ was caused by magnetic saturation because magnetic saturation was easily generated in the $q$-axis. In contrast, the change of $\hat{R}$ was too large to be caused solely by thermal changes. It is considered
that the change of $\hat{R}$ was caused by the non-linearity of the motor. The reason is as follows. In the proposed method, the actual motor is treated as the model shown in (1). The model does not take into account non-linearity, e.g., mutual inductances between the $d$-axis and $q$-axis, saturation, and core losses. Inasmuch as the model represents only the relation of input and output (voltages and currents), differences between the actual motor and the motor model are generated by several kinds of non-linearity. Although the identified resistance $\hat{R}$ changed from 0.3 $\Omega$ in Fig. 5 to 1.1 $\Omega$ in Fig. 6, we cannot know if the actual resistance changed like that. Inasmuch as the objective of parameter identification is to identify motor parameters used in position estimation to maintain accuracy, the difference between the actual resistance and the identified one is a significant problem, especially when accuracy of position estimation using identified parameters falls. However, the position estimation error is known to be suppressed in both conditions.

5. CONCLUSIONS

In this paper, an online parameter identification method is proposed. The proposed method does not require prior parameter measurements and can identify motor parameters without rotor position information. Therefore, identified parameters are not affected by the accuracy of position estimation. The proposed method was experimentally verified as useful in both SPMSMs and IPMSMs.

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