Sensorless Control of Permanent-Magnet Synchronous Motors Using Online Parameter Identification Based on System Identification Theory

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***Abstract*—An online parameter identification method and sensorless control using identified parameters were realized in 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 can be applied to all kinds of synchronous motors. The effectiveness of the proposed method was verified by experiments in both SPMSMs and IPMSMs.**

***Index Terms*—Extended electromotive force (EEMF), online parameter identification, permanent-magnet synchronous motor (PMSM), sensorless control.**

I. Introduction

SYNCHRONOUS motors are widely used in industrial applications because of their high efficiency. There are mainly three kinds of synchronous motors, namely: 1) surface permanent-magnet synchronous motors (SPMSMs), 2) interior permanent-magnet synchronous motors (IPMSMs), and 3) synchronous reluctance motors (SynRMs). PMSMs have become especially widespread, and many studies on the PMSMs have been reported. 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., 1) those using high-frequency voltage or current signals [3]–[15] and 2) those using the fundamental components of voltage and current signals [3], [10], [16]–[30]. The former methods use relations among three-phase currents [3], injection of high-frequency signals of voltages or currents [4]–[6], [10], [11], [13], [14], special inverter pulsewidth modulation (PWM) patterns [7], current response of step voltages [8], [9], information on harmonic reactive power [12], and a system identification method [15] 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.

On the contrary, the latter methods based on fundamental components were proposed starting about 20 years ago [16], and many methods have been proposed. Early methods use detected terminal information on electromotive force (EMF) [17], information on phase of flux [19], [23], difference of currents or voltages [20], [22], and a sliding observer for flux estimation [21] 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 [25], which is a mathematical model of synchronous motors, has been proposed for position estimation in IPMSMs. Inasmuch as both 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 realized for all kinds of synchronous motors. Several reports [26]–[30] have described the usefulness of the EEMF model.

Sensorless control methods based on EEMF require motor parameters to estimate rotor position just as other methods. Inasmuch as 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 [30], [31]. However, parameter measurements are cumbersome and difficult. It is hoped that these parameters can be measured online under sensorless control.

To solve this problem, several parameter identification methods under sensorless control have been proposed [32]–[36]. Some methods identify motor parameters using special

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signals at a standstill state [33] or under certain load conditions [34]. In these cases, it is difficult both to identify motor parameters under motor control and to respond to changes in these parameters. Other methods can identify motor parameters online [35], [36]. In one method [35], the accuracy of identified parameters depends on the estimation accuracy because rotor position and velocity are used to identify motor parameters. In another method [36], the stator resistance and the back EMF constant are identified, but inductances cannot be identified.

In this paper, an online parameter identification method and a sensorless control method using identified parameters are proposed to maintain position estimation accuracy, and sensorless control is realized in both SPMSMs and IPMSMs. Inasmuch as the proposed identification method does not use position and velocity to identify motor parameters, identified parameters are not affected by the accuracy of position estimation under sensorless control. Prior parameter measurements are not necessary using the proposed method. Although the proposed method requires signal injection to identify motor parameters, the method can use any signal that satisfies the condition of persistent excitation [37]. Therefore, convenient signals for motor control can be used.

This paper is organized as follows. First, the EEMF model is defined, and a serious problem in sensorless control is indicated. Next, a sensorless control method based on the EEMF is presented. Then, an online parameter identification method and a parameter derivation method that are independent of position and velocity are proposed. Finally, the effectiveness of the proposed sensorless control system is verified by experimental results for both SPMSMs and IPMSMs.

II. EEMF Model and Consideration in Parameter Variations

A. Definition of Coordinates and Symbols

Coordinates are defined in Fig. 1. The $\alpha-\beta$ frame is defined as the stationary reference frame, the *d*–*q* frame is defined as the rotating reference frame, and the $\gamma-\delta$ frame is defined as the estimated rotating reference frame.

The symbols used in this paper are as follows:

$[v_d \quad v_q]^T$ voltages on the rotating reference frame;
$[i_d \quad i_q]^T$ currents on the rotating reference frame;
$[v_\alpha \quad v_\beta]^T$ voltages on the stationary reference frame;
$[i_\alpha \quad i_\beta]^T$ currents on the stationary reference frame;
$[e_\alpha \quad e_\beta]^T$ EEMF on the stationary reference frame;
$[v_\gamma \quad v_\delta]^T$ voltages on the estimated rotating reference frame;
$[i_\gamma \quad i_\delta]^T$ currents on the estimated rotating reference frame;
R stator resistance;
K_E back EMF constant;
L_d *d*-axis inductance;
L_q *q*-axis inductance;
L rotor inductance (nonsalient-pole motor);
p differential operator;
ω_{re} angular velocity at electrical angle;

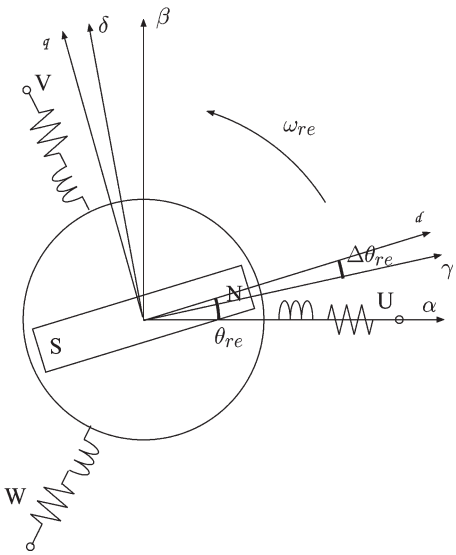

Fig. 1. Coordinates of PMSMs.

ω_{rm} mechanical rotational velocity;
θ_{re} rotor position at electrical angle;
$\Delta\theta_{\mathrm{re}}$ position estimation error;
ΔT sampling period of identification system;

$$\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$
$$\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$
$$\mathbf{O} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$
$$\mathbf{Q}(2\theta_{\mathrm{re}}) = \begin{bmatrix} \cos 2\theta_{\mathrm{re}} & \sin 2\theta_{\mathrm{re}} \\ \sin 2\theta_{\mathrm{re}} & -\cos 2\theta_{\mathrm{re}} \end{bmatrix}$$
$$\mathbf{S}(2\theta_{\mathrm{re}}) = \begin{bmatrix} -\sin 2\theta_{\mathrm{re}} & \cos 2\theta_{\mathrm{re}} \\ \cos 2\theta_{\mathrm{re}} & \sin 2\theta_{\mathrm{re}} \end{bmatrix}.$$

B. Definition of an EEMF Model

A mathematical model of synchronous motors on the rotating reference frame is written as (1). L_d is equal to L_q in SPMSMs.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega_{\mathrm{re}} L_q \\ \omega_{\mathrm{re}} L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_{\mathrm{re}} K_E \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (1)$$

By transforming (1) to the equation on the stationary reference frame, (2) is derived.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \{R\mathbf{I} + p\,(L_0\mathbf{I} + L_1\mathbf{Q}(2\theta_{\mathrm{re}}))\} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \omega_{\mathrm{re}} K_E \begin{bmatrix} -\sin \theta_{\mathrm{re}} \\ \cos \theta_{\mathrm{re}} \end{bmatrix} \quad (2)$$

where

$$L_0 = \frac{(L_d + L_q)}{2}$$
$$L_1 = \frac{(L_d - L_q)}{2}.$$

As shown in (2), there are two terms including position information $\theta_{\rm re}$. One is the back EMF term that includes $\theta_{\rm re}$ and is generated by a permanent-magnet, and the other is the $\mathbf{Q}(2\theta_{\rm re})$ term that includes $2\theta_{\rm re}$ and is generated by rotor saliency. Inasmuch as position estimation using information on both terms is very complicated and difficult, conventional position estimation methods usually use just one of these terms, rotor saliency or back EMF. In this case, position information is not fully utilized for position estimation, and it becomes necessary to switch sensorless control methods according to the kind of motor.

To solve this problem, an EEMF model [25] 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, $\dot{i}_q$ represents a differential of the *q*-axis current.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R+pL_d & -\omega_{\rm re}L_q \\ \omega_{\rm re}L_q & R+pL_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \left\{(L_d-L_q)(\omega_{\rm re}i_d-\dot{i}_q)+\omega_{\rm re}K_E\right\} \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (3)$$

By transforming (3) to the one on the stationary reference frame, (4) is derived

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = (R+pL_d)\mathbf{I}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} - \omega_{\rm re}(L_d-L_q)\mathbf{J}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \left\{(L_d-L_q)(\omega_{\rm re}i_d-\dot{i}_q)+\omega_{\rm re}K_E\right\} \begin{bmatrix} -\sin\theta_{\rm re} \\ \cos\theta_{\rm re} \end{bmatrix}. \quad (5)$$

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. Position information on both the permanent-magnet and rotor saliency can be utilized for position estimation using the EEMF model, and thereby, the sensorless control methods can be applied to all kinds of synchronous motors. The EEMF model has been used in several works [26]–[30] and is also used for position estimation in this paper.

C. *Effect of Parameter Variations and Countermeasures Against It*

These mathematical models are derived on the assumption that the motor parameters of the models are constant. However, motor parameters in actual motors vary according to magnetic saturation and thermal changes in actual motors. Differences between actual parameters and ones 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 identification method injects high-frequency signals and identifies varying motor parameters online; the position estimation system can use these identified parameters to estimate rotor position.

The proposed method has three advantages. 1) Position and velocity are not used to identify motor parameters. Therefore, identified parameters are not affected by a position estimation error under sensorless control. 2) Motor parameters can be identified online; thus, prior parameter measurements are not necessary. 3) The proposed method can use any signal that satisfies the condition of persistent excitation [37], and special bandpass filters are not necessary.

The proposed identification method will be discussed in Section IV, and a position estimation method based on the EEMF and necessary parameters will be discussed in Section III.

III. Position and Velocity Estimation Based on the EEMF

A. *Derivation of a Linear State Equation*

From (4), the linear state equation on the stationary reference frame is derived as

$$\frac{d}{dt}\begin{bmatrix} \mathbf{i} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} \\ \mathbf{O} & \mathbf{A}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{i} \\ \mathbf{e} \end{bmatrix} + \begin{bmatrix} \mathbf{B}_1 \\ \mathbf{O} \end{bmatrix}\mathbf{v} + \begin{bmatrix} \mathbf{O} \\ \mathbf{W} \end{bmatrix} \quad (6)$$

where

$$\begin{aligned}
\mathbf{i} &= [i_\alpha \quad i_\beta]^T \\
\mathbf{v} &= [v_\alpha \quad v_\beta]^T \\
\mathbf{e} &= [e_\alpha \quad e_\beta]^T \\
\mathbf{A}_{11} &= \left(-\frac{R}{L_d}\right)\mathbf{I} + \left\{\frac{\omega_{\rm re}(L_d-L_q)}{L_d}\right\}\mathbf{J} \\
\mathbf{A}_{12} &= \left(-\frac{1}{L_d}\right)\mathbf{I} \\
\mathbf{A}_{22} &= \omega_{\rm re}\mathbf{J} \\
\mathbf{B}_1 &= \left(\frac{1}{L_d}\right)\mathbf{I} \\
\mathbf{W} &= (L_d-L_q)(\omega_{\rm re}\dot{i}_d-\ddot{i}_q)\begin{bmatrix} -\sin\theta_{\rm re} \\ \cos\theta_{\rm re} \end{bmatrix}.
\end{aligned}$$

$\mathbf{W}$ is regarded as a modeling error because $\mathbf{W}$ cannot be represented as a linear state equation. This term is generated by motor current changes, and it affects position estimation when the current change rate is large. In the proposed parameter identification method, the disturbance should be suppressed because signals are injected in high-frequency ranges to identify motor parameters. The disturbance is suppressed by using a second-order low-pass filter embedded in the proposed observer, as discussed in Section III-B.

B. *Minimal-Order State Observer to Estimate the EEMF*

The minimal-order state observer to estimate the EEMF is constructed using (6) and

$$\begin{aligned}
\dot{\hat{\mathbf{i}}} &= \mathbf{A}_{11}\mathbf{i} + \mathbf{A}_{12}\hat{\mathbf{e}} + \mathbf{B}_1\mathbf{v} \\
\dot{\hat{\mathbf{e}}} &= \mathbf{A}_{11}\mathbf{G}\mathbf{i} + (\mathbf{A}_{22}+\mathbf{A}_{12}\mathbf{G})\hat{\mathbf{e}} + \mathbf{B}_1\mathbf{G}\mathbf{v} - \mathbf{G}\dot{\mathbf{i}}.
\end{aligned} \quad (7)$$

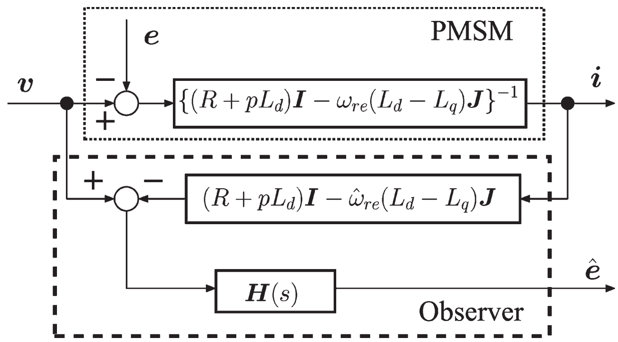

Fig. 2. Configuration of the proposed observer.

The observer can be constructed even on the estimated rotating reference frame [38] where

$$\mathbf{G} = aL_d\mathbf{I} + (\omega_{\mathrm{re}} - b)L_d\mathbf{J}.$$

Here, "ˆ" represents estimated values, $\mathbf{G}$ represents its feedback gain, and a and b represent poles of the observer, respectively. It can be seen from (7) that the observer uses R, L_d, and L_q to estimate the EEMF. In the case of SPMSMs, L_d and L_q are equal to L, and the observer uses R and L. Therefore, the proposed identification method has to identify these motor parameters.

The configuration of the observer is shown in Fig. 2. As shown in this figure, a filter $\mathbf{H}(s)$ is originally embedded in the proposed observer. This is a second-order filter, the configuration of which is

$$\mathbf{H}(s) = \frac{a}{(s+a)^2 + b^2}\left\{(s+a)\mathbf{I} + b\mathbf{J}\right\}. \tag{8}$$

The characteristics of this filter can be changed by pole assignment of the observer. A pole assignment method has been proposed to suppress the adverse effects of high-frequency disturbances on estimation of the EEMF [25]. In the proposed method, this pole assignment method is used to suppress the disturbance $\mathbf{W}$. The pole assignment is

$$\begin{aligned} a &= \nu\omega_{\mathrm{re}} \\ b &= \omega_{\mathrm{re.}} \end{aligned} \tag{9}$$

Here, ν is defined as a design parameter of the observer. When ν is set to a smaller value, the disturbance $\mathbf{W}$ can be more thoroughly suppressed, but the response of EEMF estimation is slower. Therefore, the design parameter ν must be appropriately set depending on the situation.

Here, the intermediate variable

$$\begin{aligned} \boldsymbol{\xi} &= \hat{\mathbf{e}} + \mathbf{G}\mathbf{i} \\ \dot{\boldsymbol{\xi}} &= \dot{\hat{\mathbf{e}}} + \mathbf{G}\dot{\mathbf{i}} \end{aligned} \tag{10}$$

is introduced into the observer to avoid differentiation of currents in (7).

Then, the observer is derived as

$$\begin{aligned} \dot{\boldsymbol{\xi}} &= (\mathbf{A}_{12}\mathbf{G} + \mathbf{A}_{22})\boldsymbol{\xi} + \mathbf{G}(\mathbf{A}_{11} - \mathbf{A}_{12}\mathbf{G} - \mathbf{A}_{22})\mathbf{i} + \mathbf{B}_1\mathbf{G}\mathbf{v} \\ \hat{\mathbf{e}} &= \boldsymbol{\xi} - \mathbf{G}\mathbf{i}. \end{aligned} \tag{11}$$

The EEMF is estimated by the observer, and rotor position and velocity are estimated from the phase of the estimated EEMF.

C. Position and Velocity Estimation

Rotor position θ_{re} is directly calculated from the estimated EEMF as

$$\hat{\theta}_{\mathrm{re}} = \tan^{-1}\left(\frac{-\hat{e}_\alpha}{\hat{e}_\beta}\right). \tag{12}$$

Although angular velocity can be estimated by the derivation of estimated position, a velocity-adaptive identification system used in [24] and [25] is applied in this paper because this system has the advantage of not requiring motor parameters or the derivation of the estimated position to estimate angular velocity [24], [25]. A brief explanation of the system is as follows.

This system uses the relation between the normalized EEMF $\hat{\mathbf{e}}_n$ and angular velocity ω_{re} as

$$\dot{\hat{\mathbf{e}}}_n = \omega_{\mathrm{re}}\mathbf{J}\hat{\mathbf{e}}_n \tag{13}$$

where

$$\hat{\mathbf{e}}_n = \frac{1}{\sqrt{\hat{e}_\alpha^2 + \hat{e}_\beta^2}}\begin{bmatrix}\hat{e}_\alpha \\ \hat{e}_\beta\end{bmatrix}.$$

Using this relation, the adaptive scheme of velocity is derived as

$$\dot{\tilde{\mathbf{e}}}_n = \hat{\omega}_{\mathrm{re}}\mathbf{J}\tilde{\mathbf{e}}_n + g\mathbf{I}\boldsymbol{\epsilon} \tag{14}$$

$$\hat{\omega}_{\mathrm{re}} = \left(K_P + \frac{K_I}{s}\right)(\boldsymbol{\epsilon}^T\mathbf{J}\tilde{\mathbf{e}}_n) \tag{15}$$

where

$$\boldsymbol{\epsilon} = \tilde{\mathbf{e}}_n - \hat{\mathbf{e}}_n.$$

Here, $\tilde{\mathbf{e}}_n$ represents the estimation model, $\boldsymbol{\epsilon}$ represents the EEMF error, g represents feedback gain, and K_P and K_I represent the gains of the adaptive scheme. In this method, the velocity is adjusted as the EEMF error $\boldsymbol{\epsilon}$ converges to zero. Motor parameters and differential calculations are not required to estimate the velocity.

IV. Parameter Identification Based on System Identification Theory

A. 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 can be constructed on a stationary reference frame or on an estimated rotating reference frame. In the case of parameter identification under rotation conditions, the model on the estimated rotating reference frame is better than that on the stationary reference frame because the model coefficients can be assumed to be almost constant regardless of the rotation conditions [39]. Therefore, the model is used on an estimated rotating reference frame in the proposed parameter identification method.

By transforming (1) to the one on the estimated rotating reference frame, and by transforming the equation to a discrete state equation, we have

$$\begin{bmatrix} i_\gamma(n+1) \\ i_\delta(n+1) \end{bmatrix} = \mathbf{A} \begin{bmatrix} i_\gamma(n) \\ i_\delta(n) \end{bmatrix} + \mathbf{B} \begin{bmatrix} v_\gamma(n) \\ v_\delta(n) \end{bmatrix} + \mathbf{C}[1] \quad (16)$$

where

$$\begin{aligned}
\mathbf{A} &= \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \\
&= \frac{-RL_0\Delta T + L_d L_q}{L_d L_q}\mathbf{I} + \frac{RL_1\Delta T}{L_d L_q}\mathbf{Q}(2\Delta\theta_{\mathrm{re}}) \\
&\quad + \frac{\omega_{\mathrm{re}}\left(L_d^2 + L_q^2\right)\Delta T}{2L_d L_q}\mathbf{J} - \frac{\omega_{\mathrm{re}}\left(L_d^2 - L_q^2\right)\Delta T}{2L_d L_q}\mathbf{S}(2\Delta\theta_{\mathrm{re}}) \\
\mathbf{B} &= \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \\
&= \frac{L_0\Delta T}{L_d L_q}\mathbf{I} - \frac{L_1\Delta T}{L_d L_q}\mathbf{Q}(2\Delta\theta_{\mathrm{re}}) \\
\mathbf{C} &= \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \\
&= \frac{\omega_{\mathrm{re}}K_E\Delta T}{L_q}\begin{bmatrix} \sin\Delta\theta_{\mathrm{re}} \\ -\cos\Delta\theta_{\mathrm{re}} \end{bmatrix}.
\end{aligned}$$

Equation (16) is transformed as

$$\boldsymbol{y} = \boldsymbol{\Theta}\boldsymbol{z}. \quad (17)$$

$\boldsymbol{\Theta}$ is an unknown matrix and is defined as a parameter matrix that includes motor parameters. The vectors $\boldsymbol{y}$ and $\boldsymbol{z}$ are known vectors where

$$\begin{aligned}
\boldsymbol{y} &= [\, i_\gamma(n+1) \quad i_\delta(n+1)\,]^T \\
\boldsymbol{z} &= [\, i_\gamma(n) \quad i_\delta(n) \quad v_\gamma(n) \quad v_\delta(n) \quad 1\,]^T \\
\boldsymbol{\Theta} &= [\,\mathbf{A} \quad \mathbf{B} \quad \mathbf{C}\,] = \begin{bmatrix} a_{11} & a_{12} & b_{11} & b_{12} & c_1 \\ a_{21} & a_{22} & b_{21} & b_{22} & c_2 \end{bmatrix}. \quad (18)
\end{aligned}$$

Using the relation of (17), the unknown parameter matrix $\boldsymbol{\Theta}$ can be derived from known vectors $\boldsymbol{y}$ and $\boldsymbol{z}$ by using a least square method. This method identifies the parameter matrix $\hat{\boldsymbol{\Theta}}$ as the square value of the prediction error

$$\boldsymbol{\epsilon}_i = (\boldsymbol{y} - \hat{\boldsymbol{\Theta}}\boldsymbol{z})^2 \quad (19)$$

reaches a minimum [37].

To identify the parameter matrix $\hat{\boldsymbol{\Theta}}$ online, a recursive least square method is used as shown in (20) and (21) [37]. λ is defined as the weighting coefficient, the role of which is to delete past data. From

$$\hat{\boldsymbol{\Theta}}(k) = \hat{\boldsymbol{\Theta}}(k-1) + \left(\boldsymbol{y} - \hat{\boldsymbol{\Theta}}(k-1)\boldsymbol{z}\right)\boldsymbol{z}^T\mathbf{P}(k) \quad (20)$$

$$\begin{aligned}
\mathbf{P}(k) = \frac{1}{\lambda}\Big\{&\mathbf{P}(k-1) - \mathbf{P}(k-1)\boldsymbol{z} \\
&\times \left(\lambda + \boldsymbol{z}^T\mathbf{P}(k-1)\boldsymbol{z}\right)^{-1}\boldsymbol{z}^T\mathbf{P}(k-1)\Big\} \quad (21)
\end{aligned}$$

the parameter matrix $\hat{\boldsymbol{\Theta}}$ is identified recursively.

TABLE I
CHARACTERISTICS OF MATRICES

	$x_{11}+x_{22}$	$x_{11}-x_{22}$	$x_{12}+x_{21}$	$x_{12}-x_{21}$
$\boldsymbol{I}$	2	0	0	0
$\boldsymbol{J}$	0	0	0	-2
$\boldsymbol{Q}(2\Delta\theta_{re})$	0	$2\cos 2\Delta\theta_{re}$	$2\sin 2\Delta\theta_{re}$	
$\boldsymbol{S}(2\Delta\theta_{re})$	0	$-2\sin 2\Delta\theta_{re}$	$2\cos 2\Delta\theta_{re}$	

B. Characteristics of the Parameter Matrix

Inasmuch as the parameter matrix $\boldsymbol{\Theta}$ is very complicated, it is difficult to derive motor parameters from it without using information on rotor position and velocity. If information on position and velocity is necessary to derive motor parameters under sensorless control, estimated position and velocity are substituted for actual values. In this case, it is possible that the accuracy of the derived parameters depends on the accuracy of position estimation. To solve this problem, position and velocity terms in the parameter matrix $\boldsymbol{\Theta}$ are eliminated by using characteristics of the parameter matrix $\boldsymbol{\Theta}$.

$\boldsymbol{\Theta}$ consists of four matrices, namely: 1) $\mathbf{I}$, 2) $\mathbf{J}$, 3) $\mathbf{Q}(2\Delta\theta_{\mathrm{re}})$, and 4) $\mathbf{S}(2\Delta\theta_{\mathrm{re}})$. Here, $\mathbf{I}$ represents a unit matrix, $\mathbf{J}$ represents a $\pi/2$-radian rotation matrix, $\mathbf{Q}(2\Delta\theta_{\mathrm{re}})$ represents the matrix by which arbitrary points on a two-dimensional plane are moved symmetrically to the straight line of the $\Delta\theta_{\mathrm{re}}$ radian, and $\mathbf{S}(2\Delta\theta_{\mathrm{re}})$ represents the matrix that moves points symmetrically to the straight line of the $(\Delta\theta_{\mathrm{re}} + \pi/4)$ radian. Characteristics of $\mathbf{S}(2\Delta\theta_{\mathrm{re}})$ are confirmed by the transformation

$$\mathbf{S}(2\Delta\theta_{\mathrm{re}}) = \begin{bmatrix} \cos 2\left(\Delta\theta_{\mathrm{re}} + \frac{\pi}{4}\right) & \sin 2\left(\Delta\theta_{\mathrm{re}} + \frac{\pi}{4}\right) \\ \sin 2\left(\Delta\theta_{\mathrm{re}} + \frac{\pi}{4}\right) & -\cos 2\left(\Delta\theta_{\mathrm{re}} + \frac{\pi}{4}\right) \end{bmatrix}. \quad (22)$$

Inasmuch as these matrices are well characterized as mentioned above, these characteristics should be utilized to derive motor parameters. If the four matrices are represented as shown in (23), addition and subtraction of both diagonal and nondiagonal components of these matrices can be represented as shown in Table I.

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{bmatrix} \qquad (\mathbf{X} = \mathbf{I}, \mathbf{J}, \mathbf{Q}(2\Delta\theta_{\mathrm{re}}), \mathbf{S}(2\Delta\theta_{\mathrm{re}})). \quad (23)$$

C. Parameter Derivation From the Parameter Matrix

Using the relation in Table I, motor parameters can be derived without using position and velocity data. The process of elimination of position and velocity terms is as

$$\begin{aligned}
M_1 &= b_{11} + b_{22} = \frac{2L_0\Delta T}{L_d L_q} \\
M_2 &= a_{11} + a_{22} - 2 = \frac{-2RL_0\Delta T}{L_d L_q} \\
M_3 &= \sqrt{(b_{11} - b_{22})^2 + (b_{12} + b_{21})^2} = \frac{-2L_1\Delta T}{L_d L_q}. \quad (24)
\end{aligned}$$

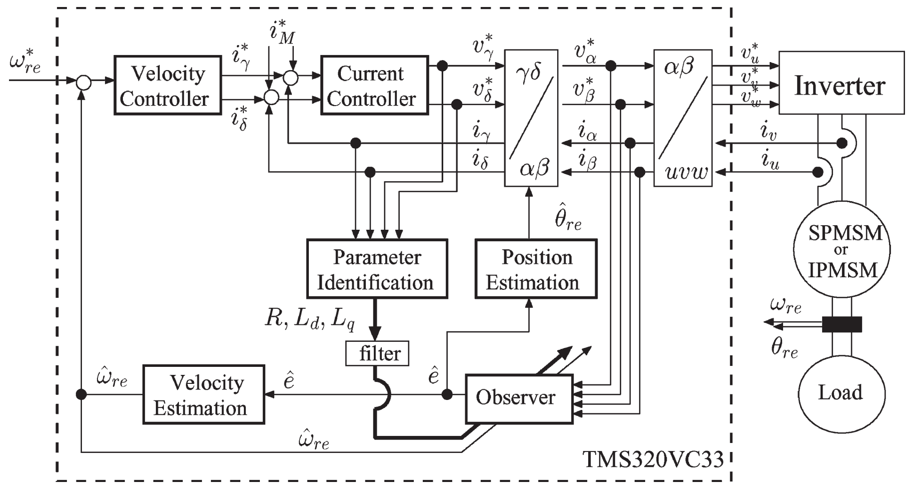

Fig. 3. Configuration of the experimental system.

Using the intermediate variables M_1, M_2, and M_3, motor parameters are derived as

$$\hat{R} = \frac{-M_2}{M_1}$$
$$\hat{L}_d = \frac{2\Delta T}{M_1 + M_3}$$
$$\hat{L}_q = \frac{2\Delta T}{M_1 - M_3}. \qquad (25)$$

In this case, information on position and velocity is not used in (24) and (25); thus, the motor parameters can be derived independently of a position estimation error.

It is appropriate for sensorless control to use these parameters after they have passed through a low-pass filter because they tend to include fluctuations. The decay time constant of the low-pass filter must be appropriately decided for each parameter.

V. Experimental Results

A. Configuration of the Experimental System

Sensorless control with online parameter identification was realized using the same system in both an SPMSM and an IPMSM. Fig. 3 shows the configuration of the proposed sensorless control system. Although the estimation system was based on the EEMF model, the parameter identification system can be applied to any estimation system that uses motor parameters.

Stator currents are detected by current sensors and are then sent to a digital signal processor (DSP TMS320VC33) through 12-bit analog-to-digital (A/D) converters. Three-phase current signals and voltage references are transformed to two-phase signals on the stationary reference frame, and these signals are transformed to those on 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. Using these identified parameters, the proposed observer estimates the EEMF, which, in turn, estimates the position and velocity.

TABLE II
Specifications of SPMSM and IPMSM

Rated power	0.5 [kW]
Rated current	5.0 [A]
Rated speed	2500 [r/min]
Back EMF constant (SPMSM)	1.15 [V/(rad/s)]
Back EMF constant (IPMSM)	1.04 [V/(rad/s)]
Number of pole pairs	2
DC link voltage	130 [V]
Inverter switching frequency	5 [kHz]
Sampling period	200 [μs]

The velocity controller is a polarization index (PI) controller; it outputs current references from the current phase angle and a velocity control error between the estimated velocity and the velocity reference. The current phase angle is set appropriately in each motor. Then, i_M^* is added to each current reference. i_M^* represents the injection signals required to identify motor parameters, and *M*-sequence signals [40] are chosen for i_M^*. *M*-sequence signals are pseudorandom sequence signals often used in system identification. Although *M*-sequence signals are used as i_M^* in this paper, any signal that satisfies the condition of persistent excitation can be used [37]. The current controller consists of two PI controllers for each axis and outputs voltage references from current control errors between reference values and measured ones. In addition, coupling terms in each axis are added to voltage references to decouple the *d*-axis and the *q*-axis.

Table II shows specifications of the two test motors, i.e., 1) an SPMSM and 2) an IPMSM. The ratio of the amplitude of *M*-sequence signals to the rated current is about 6% in the two motors. Of course, it is not necessary to inject these signals when the parameters need not be identified.

B. Position Estimation Results

Fig. 4 shows the results of position estimation at no load in the IPMSM. $\theta_{\rm re}$ represents the measured position at the electrical angle, $\hat{\theta}_{\rm re}$ represents the estimated position, and $\Delta\theta_{\rm re}$ represents the position estimation error. The reference velocity was set to 500 r/min.

It is understood based on the figure that stable position estimation using identified parameters could be realized and

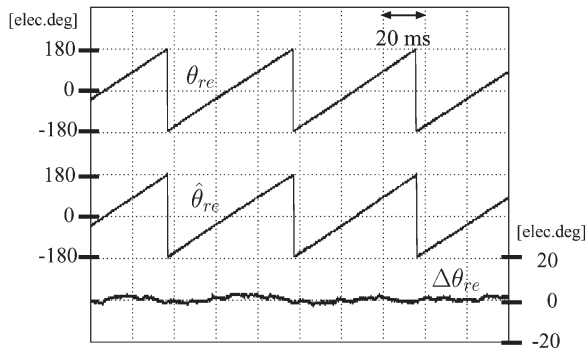

Fig. 4. Position estimation result.

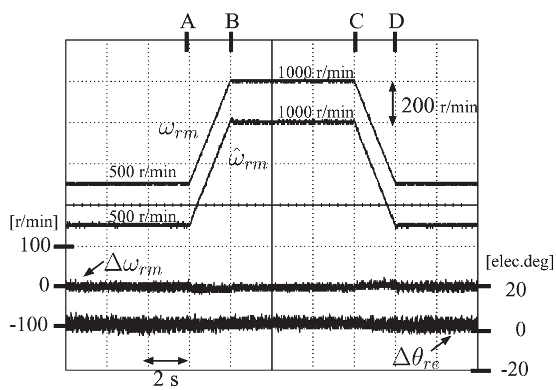

Fig. 5. Velocity estimation result under speed change.

that the position estimation error could be suppressed within 3 electrical degrees. The results in the SPMSM are the same.

C. Velocity Estimation Results

Fig. 5 shows the results of velocity estimation in the SPMSM. ω_{rm} represents the measured mechanical rotational velocity, $\hat{\omega}_{\mathrm{rm}}$ represents the estimated velocity, and $\Delta\omega_{\mathrm{rm}}$ represents the velocity estimation error. The reference velocity was changed. Beginning at 500 r/min, the reference velocity was increased from point A and was set to 1000 r/min at point B. Then, it was decreased from point C and was set back to 500 r/min again at point D.

It is understood based on the figure that stable velocity estimation and sensorless control using identified parameters could be realized under speed change conditions. The results in the IPMSM are the same.

D. Parameter Identification Results

Figs. 6 and 7 show results of parameter identification in the SPMSM. Fig. 6 shows results at no load, whereas Fig. 7 shows results at rated load (2.0 N · m). $\hat{R}$ and $\hat{L}$ represent identified parameters. The reference velocity was set to 500 r/min.

From a comparison of Figs. 6 and 7, the identified parameters in both figures were approximately the same, and precise position estimation could be realized in both conditions. Therefore, the appropriate motor parameters for position estimation could be identified using the proposed method.

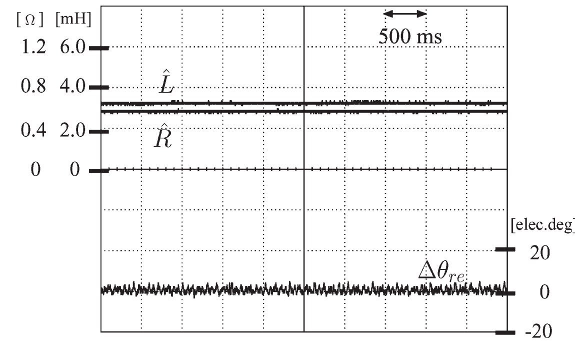

Fig. 6. Position estimation and parameter identification results at no load (SPMSM).

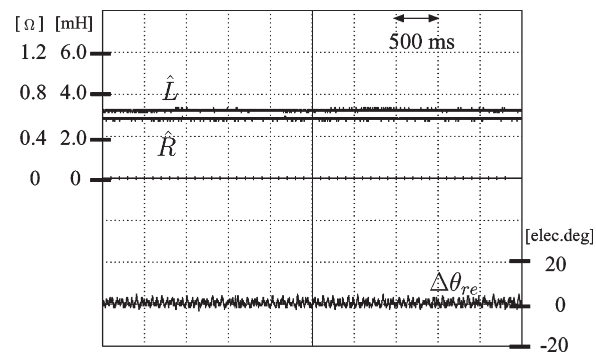

Fig. 7. Position estimation and parameter identification results at rated load (SPMSM).

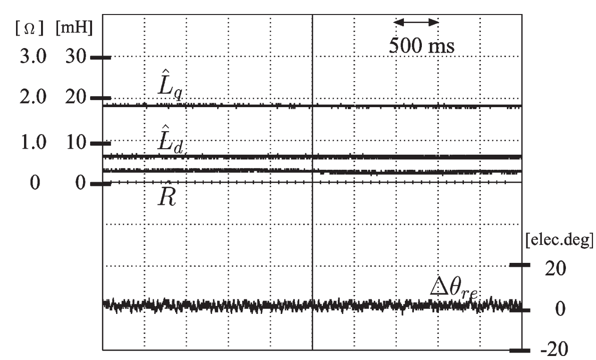

Fig. 8. Position estimation and parameter identification results at no load (IPMSM).

Figs. 8 and 9 show the results in the IPMSM. Fig. 8 shows results at no load, whereas Fig. 9 shows results at rated load (1.8 N · m). $\hat{R}$, $\hat{L}_d$, and $\hat{L}_q$ represent identified parameters. The reference velocity was set to 500 r/min.

Comparing Figs. 8 and 9, we see that the identified parameters changed. $\hat{L}_q$ changed from 18 mH at no load to 14 mH at rated load, and $\hat{R}$ changed from 0.3 Ω at no load to 1.1 Ω 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 nonlinearity 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 nonlinearity, e.g., mutual inductances between the d-axis and

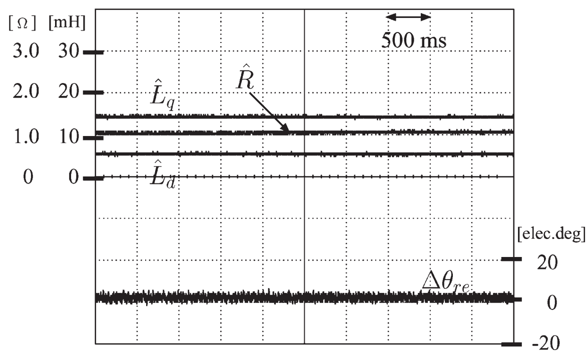

Fig. 9. Position estimation and parameter identification results at rated load (IPMSM).

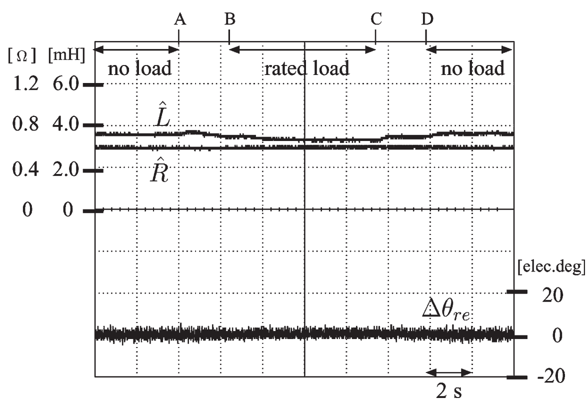

Fig. 10. Position estimation and parameter identification results under load change (SPMSM).

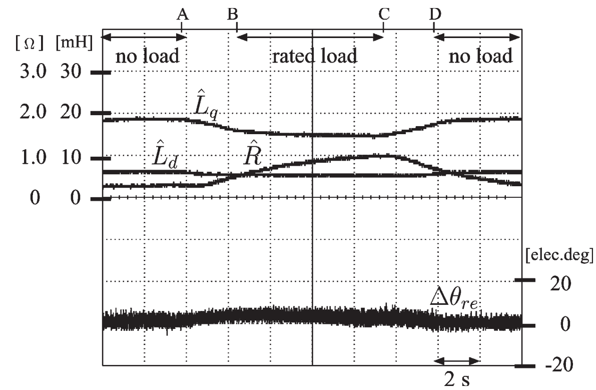

Fig. 11. Position estimation and parameter identification results under load change (IPMSM).

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 nonlinearity. These differences generate differences between actual parameters and model parameters; thus, the identified parameters might differ from actual parameters. Although the identified resistance $\hat{R}$ changed from 0.3 Ω in Fig. 8 to 1.1 Ω in Fig. 9, we cannot know whether 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, from these figures, the position estimation error is known to be suppressed in both conditions. Therefore, appropriate motor parameters for position estimation could be identified by the proposed method.

E. Sensorless Control Under Load Change

Fig. 10 shows results under load changes in the SPMSM. The velocity was set to 500 r/min.

Beginning at no load, the load was increased from point A and was set to rated load at point B. Then, it was decreased from point C and set back to no load again at point D.

In Fig. 10, identified parameters in the steady state were equal to those in Figs. 6 and 7. Therefore, appropriate motor parameters were identified regardless of load change conditions, and the position estimation error was suppressed to within 3 electrical degrees under the load change condition.

Fig. 11 shows results in the IPMSM. Velocity was set to 500 r/min. The load change condition was equal to that in Fig. 10.

In Fig. 11, $\hat{R}$ changed slowly because the speed of parameter variations was decided by the decay time constant of the low-pass filter. However, identified parameters at no load and rated load were equal to those in Figs. 8 and 9. Therefore, appropriate motor parameters were identified, and the position estimation error was suppressed to within 6 electrical degrees regardless of load change conditions.

With the use of the identified parameters, position estimation under load changes was realized.

VI. CONCLUSION

In this paper, an online parameter identification method under sensorless control was 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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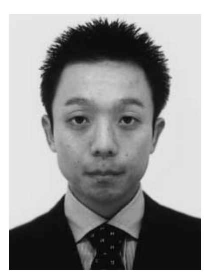

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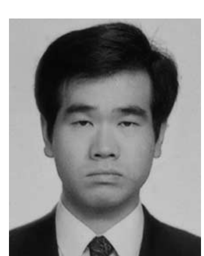

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