Investigation of Servomotor Structure for Sensorless Control Based on High-Frequency Injection Method

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This paper presents the servomotor structure suitable for sensorless drives based on high-frequency injection method. The position estimation accuracy is related to the saliency ratio of the motor. Although the motor with increasing saliency ratio with the load has been reported, the mechanism of the phenomenon has not been explained.

In this paper, the improvement in the saliency ratio in a conventional servomotor structure is explained with respect to the magnetic flux distribution. Moreover, the increase in the saliency ratio through further structural improvement is examined, and the effect is confirmed by experiments.

Keywords : sensorless drive, high-frequency injection, saliency ratio, servomotor

1. Introduction

The sensorless drive technologies are classified into two methods to detect rotor position, one is the back electromotive force (EMF) detection method⁽²⁾⁽³⁾ and the other is high-frequency injection method⁽⁴⁾⁻⁽⁷⁾. The back EMF detection method has high performance in medium and high-speed regions. But in the low speed range or zero speed the back EMF diminishes and the performance degrades. The high-frequency injection method has the advantages that it is possible to obtain sufficient torque even at low and zero speed. In addition, the position estimation method based on an extended electromotive force (EEMF) combined with signal injection method is proposed which can estimate the position in all speed regions⁽⁷⁾. In reference (9), a control method using speed observer and open phase voltages is proposed. This method can detect zero speed without high-frequency injection, but requires a circuit for open phase voltage detection. Therefore, in the industrial field, the high-frequency injection method has been adopted and has already been applied to various applications. The technology is applied not only to the rotary motor but also to the linear motor⁽¹⁰⁾.

However, the injection signal causes an increase in loss and acoustic noise. In reference (11), suppression of acoustic noise caused by voltage injection is discussed. The amplitude and frequency of the injection signal for the required position estimation accuracy depends on the saliency ratio of the motor. Therefore, the characteristics of the motor are an important factor for high-frequency injection methods.

The saliency ratio of the motor used in a high-frequency injection method depends on the motor structure. It is known that the saliency ratio becomes lower and its phase changes during load conditions. Small size and high torque density motors have a large influence on magnetic saturation, therefore, the above problems become significant. Furthermore, in the servomotor, positioning accuracy is required even under the sensorless control drive. For such problems, studies have been made on control methods and the motor structures.

The control methods considering the cross-coupling of inductances and the design of the motor are examined⁽¹²⁾⁻⁽¹⁴⁾. And the method of compensating the position estimated by using the cross-coupling components estimated from the injected high frequency signal is proposed⁽¹⁵⁾. In reference (16), a sensorless control based on the high-frequency injection is applied to a servomotor, and improvement of positioning accuracy using the correction by a look-up table is reported.

From the viewpoint of motor structures, the motor design to suppress the phase change due to the cross-coupling of inductances and the reduction in the saliency ratio due to the magnetic saturation has been studied⁽¹⁷⁾⁽¹⁸⁾. The servomotor in the reference (16) is based on a concentrated-winding IPM structure. Generally, the saliency ratio of the concentrated winding motor is small. In addition, magnetic saturation occurs with the load in the high torque density motor such as a servomotor. Therefore, a reduction of positioning accuracy and maximum torque occurs.

However, the motor shown in reference (16) has features that the saliency ratio increased with the load, and it is considered that a certain degree of magnetic saturation in this motor structure is preferable to keep saliency ratio high at load conditions. These features are not found in other motors, and the details of the phenomenon have not been explained.

In this paper, the phenomenon of increasing the saliency ratio with load is investigated by examining the magnetic flux distribution. Moreover, a motor structure is proposed for further improvement in the saliency ratio, thereby position estimation accuracy.

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2. Conventional Motor Structure

2.1 Resolution of position detection In the high frequency injection method, the minimum detection width of the position is expressed as follows⁽¹⁶⁾.

$$\Delta\theta \propto \frac{\omega_{inj} L_{dh} \cdot L_{qh}}{V_{inj} |L_{dh} - L_{qh}|} \dots\dots\dots (1)$$

where

- $\Delta\theta$: the minimum detection width of the position
- L_{dh} : d-axis high-frequency inductance
- L_{qh} : q-axis high-frequency inductance
- V_{inj} : amplitude of high-frequency injection voltage
- ω_{inj} : frequency of injection voltage

From the equation (1), it is possible to reduce the minimum detection width of the position by increasing the saliency ratio.

Fig. 1. Structure of conventional motor.

Table 1. Specifications

Rated Power	400W
Rated Speed	3000min ⁻¹
Rated Current	2.5Arms
Stator Resistance	1.36Ω
Nominal Inductance	2.99mH
Pole Number	10

Fig. 2. d,q-axis.

2.2 Characteristics of High-frequency inductance

Fig. 1 shows the motor structure used in reference (16). The structure of Fig. 1 is referred to as the conventional structure in this paper. It has a concentrated winding and Interior Permanent Magnet (IPM) structure of 10 poles 12 slots. The magnets are placed radially of the rotor, and the magnetic flux is concentrated to the pole shoe. The rotor core has air holes. Thin bridges of the rotor core exist between air holes and the magnets. The shaft side rotor core is connected by these bridge parts with pole shoe parts. The dimensions of the shape of the hole and bridge parts are decided considering magnetic saturation and a structural aspect.

Fig. 3. Relationship between injection angle and inductance. (Analysis)

Fig. 4. Relationship between injection angle and inductance. (Measurement)

Table 1 shows the specifications of the motor. Fig. 2 shows the d and q axis. Inductances are calculated using FEM under applying a high-frequency injection voltage to the winding. The 3-phase voltages of injection component expressed as

$$\begin{bmatrix} V_{u_{inj}} \\ V_{v_{inj}} \\ V_{w_{inj}} \end{bmatrix} = \begin{bmatrix} \cos \theta_{inj} & -\sin \theta_{inj} \\ \cos \left(\theta_{inj} - \frac{2}{3}\pi \right) & -\sin \left(\theta_{inj} - \frac{2}{3}\pi \right) \\ \cos \left(\theta_{inj} + \frac{2}{3}\pi \right) & -\sin \left(\theta_{inj} + \frac{2}{3}\pi \right) \end{bmatrix} \begin{bmatrix} V_h \\ 0 \end{bmatrix} \dots\dots\dots (2)$$

Where

- $V_h = V_{inj} \sin(\omega_{inj} t)$
- $V_{u_{inj}}, V_{v_{inj}}, V_{w_{inj}}$: injection voltage of U, V, W phase
- θ_{inj} : injection angle

The rotor and stator positions are set and fixed as shown in Fig. 2. The frequency of the injection voltage is set to 1 kHz and the amplitude is set to 30V_{rms}.

The d-axis and q-axis currents of injection component are expressed as

$$\begin{bmatrix} I_{dh} \\ I_{qh} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta_{inj} & \cos \left(\theta_{inj} - \frac{2}{3}\pi \right) & \cos \left(\theta_{inj} + \frac{2}{3}\pi \right) \\ -\sin \theta_{inj} & -\sin \left(\theta_{inj} - \frac{2}{3}\pi \right) & -\sin \left(\theta_{inj} + \frac{2}{3}\pi \right) \end{bmatrix} \begin{bmatrix} I_{uh} \\ I_{vh} \\ I_{wh} \end{bmatrix} \dots\dots\dots (3)$$

Where

- I_{uh}, I_{vh}, I_{wh} : high-frequency currents of U, V, W phase
- I_{dh}, I_{qh} : high-frequency currents of d, q phase

High frequency inductance L_h is expressed as follows;

$$L_h = \frac{V_{inj}}{\omega_{inj} I_{dh}} \dots\dots\dots (4)$$

Fig. 5. Distribution of Magnetic flux and Contour of Magnetic flux density.

Fig. 6. Magnetic flux distribution of high-frequency component. ($\theta_{inj} = 90^\circ$)

Fig. 7. Magnetic flux distribution of high-frequency component. ($\theta_{inj} = 0^\circ$)

Fig. 3 and Fig.4 show the analysis and measurement results of the high-frequency inductances respectively. Both results show a good agreement. The high-frequency inductance of the maximum value is increased with the load current increase. The reason why the saliency ratio increases with the load can be explained based on magnetic flux distribution.

Fig. 5 (a) and (b) shows the distribution of the main magnetic flux and the contour of magnetic flux density at no load and 200% load respectively. The tip part of the stator teeth has a high magnetic flux density even at no load. Although the magnetic flux density of the motor is high at load, the magnetic flux density of a part of the motor such as the stator teeth tip becomes low, and the saturation level mitigates.

Fig. 6 and Fig. 7 show distributions of high-frequency flux components when the injection angles are $\theta_{inj} = 90^\circ$ and 0° respectively. To confirm the flow of the magnetic flux caused only by the high-frequency current, load field components produced by excitation sources need to be separated. So, a high-frequency current $I_h = 1A$ is applied, and the high-frequency flux distribution

is calculated as the difference before and after injecting the high-frequency current I_h .

Fig. 6 is a case that the injection angle of the high-frequency current is set to 90° which corresponds to the state of 90° in Fig. 2. Fig. 6 (a) and (b) are cases when a high-frequency current is applied at no load and 200% load respectively. In Fig.6 (a), the high-frequency magnetic flux passes through the rotor pole shoe surface. This shows the distribution of magnetic flux of the so-called q-axis component. In Fig. 6 (b), the high-frequency magnetic flux at load passes through the stator teeth tip part that magnetic saturation is relaxed. Therefore, the amount of high-frequency magnetic flux component is increased. The phenomenon that the q-axis high-frequency magnetic flux becomes higher at load is considered to be due to saturation relaxation of the magnetic flux density by the main magnetic flux. Although details are not mentioned in this paper, magnetic flux passes not only to the rotor pole shoe surface but also to the next pole at load. The magnetic flux is related to the so-called cross-coupling and phase shift.

Fig. 7 is a case of the injection angle of the high-frequency current is set to 0° , which corresponds to 0° in Fig. 2. High-frequency magnetic flux corresponds to the d-axis magnetic flux. Changes in the magnetic flux distribution at load are small compared with the one at no-load. So, it is not affected much load current. The high-frequency magnetic flux flows the same path as the main magnetic flux. Therefore, by adjusting the magnetic flux density of the main magnetic flux in the stator teeth part, it is considered possible to suppress the amount of the high-frequency magnetic flux and reduce the L_h at 0° .

3. Proposed Motor Structure

Fig. 8 shows the proposed structure. The grooves are provided in the stator teeth. It can be expected that the d-axis component of the high-frequency magnetic flux is suppressed by provided grooves.

Fig. 9 shows the analysis results of the high-frequency inductance and Fig. 10 shows the measurement results. Both results show a good agreement. In the case of the proposed structure, the maximum value of the high-frequency inductance is also increased with the load current increase. The maximum value of inductances shows the same value as the conventional structure. The inductance at around $\theta_{inj} = 0^\circ$ is reduced in the analysis. It is the effect of the groove. In the measurements, the difference from the conventional structure is small, but the value has also decreased by the provided groove.

Fig. 8. Structure of proposed motor.

Fig. 9. Relationship between injection angle and inductance. (Analysis)

Fig. 10. Relationship between injection angle and inductance. (Measurement)

Fig. 11. Distribution of magnetic flux and contour of magnetic flux density.

Fig. 12. High-frequency component of magnetic flux. ($\theta_{inj} = 90^\circ$)

Fig. 13. High-frequency component of magnetic flux. ($\theta_{inj} = 0^\circ$)

Fig. 14. Characteristic of saliency.

Fig. 11 shows the distribution of the main magnetic flux. The magnetic flux density is locally higher around the groove in the stator teeth part. Fig. 12 and 13 show high-frequency flux distributions. Fig. 12 shows the case of the $\theta_{inj} = 90^\circ$ and Fig. 13 is the case of $\theta_{inj} = 0^\circ$. The tendency of the flow pattern of the high-frequency magnetic flux is the same as the conventional structure. In the case of $\theta_{inj} = 0^\circ$, the amount of magnetic flux is reduced, and the L_h is considered to be decreased.

Fig. 14 shows the saliency ratio characteristics according to the load. Here, the saliency ratio is a ratio between the maximum value and the minimum value of the high-frequency inductances shown in Fig. 9 and Fig. 10. The saliency of the proposed structure is increased compared with the conventional structure. In the conventional structure, the measurement and analysis results are in good agreement. In the improved structure, the saliency ratio increases with the load in the analysis, but it remains almost constant in the measurement. The reason that the measured value of d-axis inductance is larger than the analysis value, the influence of magnetic saturation is different in the actual machine and the analysis.

Table 2 shows the values of L_{dh} and L_{qh} at no load. L_{dh} is the value at $\theta_{inj} = 0^\circ$, and L_{qh} is the value at $\theta_{inj} = 90^\circ$ in Fig. 3, 4, 9 and 10. By substituting these inductance values into the equation (1), the minimum detection width of the position can be calculated. The proposed structure's one is approximately 25% smaller in the analysis and approximately 40% smaller in the measurement than the conventional structure. Significant improvements can be expected. Table 3 shows the value of L_{dh} and L_{qh} at 200% load. These values are not minimum and maximum values. The positions of maximum and minimum deviate from $\theta_{inj} = 0^\circ$ and 90° owing to the cross-coupling phenomenon. However, the saliency ratio almost

Table 2. Inductance parameter (at no-load)

	Analysis(mH)		Measure(mH)	
	L_{dh}	L_{qh}	L_{dh}	L_{qh}
θ_{inj}	0	90	0	90
conventional	2.7	3.1	2.6	3.1
proposed	1.9	3.0	2.3	3.5

Table 3. Inductance parameter (at 200%Load)

	Analysis(mH)		Measure(mH)	
	L_{dh}	L_{qh}	L_{dh}	L_{qh}
θ_{inj}	0	90	0	90
conventional	2.6	3.4	2.7	3.5
proposed	1.8	3.2	2.5	3.1

Fig. 15. EMF wave form.

Fig. 16. Harmonic components of EMF waveform.

same value compared the one at no-load.

Fig. 15 and Fig. 16 shows the electromotive force (EMF) waveform and harmonic components respectively. The EMF of the proposed motor decreased by 10% compared with the conventional one. So, in order to obtain the same output power, it is necessary to increase the current by 10%. The size of grooves affects the magnetic saturation of stator teeth, which determines the reduction of d-axis inductance and EMF. Since the relation between saliency ratio and EMF is a trade-off relation. The size of grooves' length and depth are decided using FEM analysis so that saliency ratio becomes large as much as possible within the allowable range of EMF decrease. However EMF of the proposed motor decreases, sensorless drive performance can be greatly improved.

Fig. 17 shows a change due to the position of the line-inductance. In the control method of the d-axis search type, the minimum portion of the inductance is recognized as the d-axis at the initial position estimation.

If the minimum portion of the inductance is flat, the estimated position error of the d-axis increases. In the proposed structure, it

(a) Analysis

(b) Measurement

Fig. 17. Relationship between rotor position and inductance.

becomes more to sinusoidal, and improvement of the initial position estimation can be expected. The difference between the maximum value and the minimum value is also increased, the saliency ratio is increased.

Fig. 17 (b) shows the measured value. Although the distortion is smaller than the analysis in the conventional structure, it can be seen that the saliency ratio is increased in the proposed structure.

4. Experiment

4.1 Control method Fig. 18 shows a control block diagram. The position estimation method using a square wave voltage synchronized with PWM⁽¹⁶⁾⁽¹⁹⁾ is applied. The method is described below.

The voltage equation in the synchronous reference frame (rotor d-q coordinate system) is expressed as

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + L_d p & -\omega L_q \\ \omega L_d & R + L_q p \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \phi \end{bmatrix} \dots \dots \dots (5)$$

where v_d and v_q are d-axis and q-axis voltages, respectively, R is electric resistance of one phase, L_d and L_q are d-axis and q-axis inductances, respectively, ϕ is d-axis linkage magnetic flux, $p = d/dt$ is a differential operator of time, and ω is rotation angular speed in electrical radian per seconds.

If the frequencies of injected voltage and current are much higher than the synchronous frequency of the motor, product terms of inductance and differentiated current are much more significant than other terms in equation (5). Thus, equation (5) can be

Fig. 18. Control block diagram

approximated as

$$\begin{bmatrix} v_{dh} \\ v_{qh} \end{bmatrix} = \begin{bmatrix} L_{dh}p & 0 \\ 0 & L_{qh}p \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} = [Z_{dq}] \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \quad \dots\dots\dots(6)$$

where subscript “h” means that the value is concerned with high-frequency signal.

When a pulsating voltage is injected into the d-axis of the estimated rotor reference frame, injected high-frequency voltage can be described as in equation (7).

$$\begin{bmatrix} v_{dh} \\ v_{qh} \end{bmatrix} = \begin{bmatrix} V_{inj} \cos \omega_h t \\ 0 \end{bmatrix} \quad \dots\dots\dots(7)$$

where V_{inj} is the magnitude and ω_h is the angular frequency of injection voltage.

Transforming equation (6) to the stationary reference frame as shown in equation (8).

$$\begin{aligned} \begin{bmatrix} i_{ah} \\ i_{bh} \end{bmatrix} &= [\mathbf{R}(\theta_r)]^{-1} [Z_{dq}]^{-1} [\mathbf{R}(\theta_r)] \begin{bmatrix} v_{dh} \\ v_{qh} \end{bmatrix} \\ &= [\mathbf{R}(\theta_r)]^{-1} [Z_{dq}]^{-1} \begin{bmatrix} v_{dh} \\ v_{qh} \end{bmatrix} \quad \dots\dots\dots(8) \end{aligned}$$

where θ_r is the rotor position, $\mathbf{R}$ is the rotation matrix.

Assuming that the estimation error of the rotor position is small enough, then equation (8) is simplified to equation (9).

$$\begin{aligned} \begin{bmatrix} i_{ah} \\ i_{bh} \end{bmatrix} &= [\mathbf{R}(\theta_r)]^{-1} [Z_{dq}]^{-1} \begin{bmatrix} V_{inj} \cos \omega_h t \\ 0 \end{bmatrix} \\ &= \frac{V_{inj} \sin \omega_h t}{L_{dh} \omega_h} \begin{bmatrix} \cos \theta_r \\ \sin \theta_r \end{bmatrix} \quad \dots\dots\dots(9) \end{aligned}$$

Therefore, the rotor position $\hat{\theta}_{rh}$ can be estimated by the arctangent operation as follows.

$$\hat{\theta}_{rh} = \tan^{-1} \left(\frac{\frac{i_{bh}}{\sin \omega_h t}}{\frac{i_{ah}}{\sin \omega_h t}} \right) \quad \dots\dots\dots(10)$$

The currents i_{ah} and i_{bh} are obtained from the detected current through a Band Pass Filter of the superimposed frequency components. Further, the Low Pass Filter is required to remove the noise component at the position detected by equation (10). However, since the servo system requires responsiveness, it is necessary to reduce the delay in position calculation. Therefore a method to inject square wave voltage in d-axis of the estimated rotor reference frame is proposed⁽¹⁶⁾. The injected voltage can be described as following equation (11).

$$V_h[n] = \begin{cases} V_{inj}, & n = 2m \\ -V_{inj}, & n = 2m + 1 (m = 0, 1, 2, \dots) \end{cases} \quad \dots\dots\dots(11)$$

Fig. 19 shows the square wave voltage and its response current. The current response to the square wave voltage changes like a triangular wave by referring to the switching point of the square

Fig. 19. Waveforms of the PWM voltage and injected voltage and the response current.

Fig. 20. Experimental system configuration

Table 4. Specification of Servo Driver A

Output Power	W	400
Rated Voltage	Vrms	200
Rated Current	Arms	2.9
Carrier Frequency	kHz	10
Injection signal frequency	kHz	10
Injection signal voltage	Vrms	100
Position control gain	1/s	40

wave that is the sampling point. As shown in equation (12), the envelope ($I_{\cos}[n]$, $I_{\sin}[n]$) of high frequency current components can be extracted by multiplying the difference of the current for each sampling by the sign of the injection voltage.

$$\begin{bmatrix} I_{\cos}[n] \\ I_{\sin}[n] \end{bmatrix} = \text{sign}(V_h[n]) \begin{bmatrix} i_{ah}[n] - i_{ah}[n-1] \\ i_{bh}[n] - i_{bh}[n-1] \end{bmatrix} \quad \dots\dots(12)$$

From the envelope obtained by (12), the position $\hat{\theta}_{rh}[n]$ can be estimated as in equation (13).

$$\hat{\theta}_{rh} = \tan^{-1} \left(\frac{I_{\sin}[n]}{I_{\cos}[n]} \right) \quad \dots\dots\dots(13)$$

The envelope operation of equation (12) is more robust to noise compared to equation (9), so no filter is necessary. Therefore, the delay in position estimation can be reduced.

However, this method estimates the minimum portion of inductance as d-axis, so the positioning error increases depending on the load. In order to reduce the position estimation error at load, the position compensation method using the approximation function of the position estimation error by the torque command⁽¹⁶⁾ is adopted. Alternatively, similar results can be achieved by applying a position compensation method based on the cross-coupling factor⁽¹³⁾⁽¹⁵⁾.

4.2 Experimental system and measurement method

Fig. 20 shows the experimental system. Servo Driver A controls the rotor position of the motor by sensorless control. However, the position compensation is not used because the effect of improving the saliency ratio is evaluated in this experiment. The measurement PC gives a position command to Servo Driver A and collects the estimated position from Servo Driver A.

(a) Conventional structure

(b) Proposed structure
Fig. 21. Positioning error

Table 5. Experimental results of positioning error.

Motor structure	conventional	proposed
Positioning error	$\pm 20^\circ$	$\pm 5^\circ$

The motor is equipped with a 24 bits position sensor. Servo Driver B detects the rotor position from the signal of the position sensor, and the detected rotor position data is collected by the measurement PC. The measurement PC calculates the difference between the estimated rotor position and the detected rotor position after positioning the rotor as a positioning error. Here, positioning means that the estimated feedback position by sensorless control coincides the position command.

Table 4 shows the specification of Servo Driver A including high frequency injection condition. The injection signal is 1kHz and 30V in the simulation, but is set to 10kHz and 100V in the experiment. This is to obtain sufficient position detection performance even with a conventional motor having a low saliency ratio.

4.3 Measured result Fig. 21 shows the positioning error. The motor has 10 poles, and one mechanical angle period is equivalent to five electrical angle periods. In Fig. 21, the positioning error is shown for one electric period.

Table 5 shows the experimental results of the positioning error. The positioning error of the conventional structure has a maximum of $\pm 20^\circ$, whereas the proposed structure has maximum of about $\pm 5^\circ$, and it is approximately 25% of the conventional structure. This reduction in position error is due to the saliency ratio improvement described in the previous section.

5. Conclusion

The motor structure was investigated to improve sensorless drive performance. The phenomenon that the saliency ratio increases with the load in the conventional structure was clarified based on the magnetic flux distribution of the high frequency that it due to

local relaxation of magnetic saturation by the load current.

This paper also proposed a structure with a groove on a part of the stator teeth. In the proposed structure, it was shown that the saliency ratio is increased, and it is possible to further reduce the positioning error.

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