Audible Noise Reduction Method in IPMSM Position Sensorless Control Based on High-Frequency Current Injection

Yuki Tauchi∗a) Student Member, Hisao Kubota∗ Senior Member

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Methods for sensorless control involving the injection of a high-frequency signal into the low-speed range of an interior permanent-magnet synchronous motor (IPMSM) have been proposed. However, audible noise is a concern for these methods. We propose a method to reduce the audible noise due to a high-frequency current by minimizing the injection-signal amplitude suitable for IPMSM driving states.

Keywords: audible noise, high-frequency, IPMSM, position sensorless control

1. Introduction

IPMSMs are often used in elevators, air conditioners, and HEVs because they are more compact and efficient as compared to induction motors. To drive an IPMSM, the pole position information is necessary. Hence, position sensors such as rotary encoders or hole-effect sensors are used. Because position sensors have disadvantages such as reduced reliability and increased costs, many sensorless control methods have been proposed (1)–(7).

Generally, sensorless control methods of IPMSM utilize the back electromotive force (EMF) that is proportional to the motor speed (2). These methods become common technologies, and the microcomputer that automatically carries out a computation (current control(ACR), coordinate transformation, etc.) for the vector control by the embedded hardware in it is available (8). When this microcomputer is used, the software to drive the IPMSM is only the estimation of the rotor position and the current command calculation.

Methods based on back EMF presents good performance in middle and high-speed range drive of the IPMSM. However, they are not able to be applied to drive of the IPMSM at low-speeds or standstill, because the back EMF is proportional to the motor speed. So, methods based on saliency of IPMSM have been proposed too (9). These methods present good performance at standstill and low-speed range drive of the IPMSM. The saliency based sensorless methods have to inject high-frequency current (10), high-frequency voltage (11–14), or pulse voltage (15). But, audible noise is a concern when a high-frequency signal is injected. In general, the high-frequency signal amplitude is maintained at a required constant value. This general approach makes a large audible noise.

To solve the problem, a method to determine the high-frequency signal amplitude from experimental results has been proposed (9). This method changes the injection signal amplitude within the range of the lower limit and the higher limit which are determined experimentally. At the transient state, the injection signal amplitude is increased to the higher limit in order that estimation performance does not deteriorate. At the steady state, the injection signal amplitude is decreased to the lower limit which does not depend on conditions such as rotational speed or load torque. In order to minimize the audible noise, the injection signal amplitude should be changed depending on conditions such as rotational speed or load torque.

In this paper, to reduce the audible noise due to the high-frequency current, we propose a method for minimizing the injection signal amplitude suitable IPMSM for without providing the lower limit setting of the high-frequency current amplitude command value. In this study, we investigated the sensorless control method based on high-frequency current injection described in (3), with a focus on the low-speed range drive of the IPMSM, because this method easily utilizes the microcomputer with the embedded ACR hardware.

The proposed method uses the error between the speed command and the estimated speed. The speed error is low at the steady state, and high at the transient state. When the estimation accuracy deteriorates, the speed error is increased in proportion to the position error. Therefore, the speed error can distinguish the driving state. The proposed method uses the speed error to determine the high-frequency current amplitude command value. So, the proposed method operates with a load change and a wide speed range. Experimental results show that the proposed method is valid.

2. High-Frequency Signal Injection Methods

In the rotating dq coordinate frame, the voltage equation of the IPMSM is represented by Eq. (1). The general technical term are shown in Appendix.

\[
\begin{bmatrix}
    v_d \\
    v_q
\end{bmatrix} =
\begin{bmatrix}
    R + pL_d & -\alpha L_d \\
    \alpha L_d & R + pL_q
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix}
\quad + \begin{bmatrix}
    0 \\
    0
\end{bmatrix}
\]

where \( p \) is a differential operator.

The estimated axes are represented by the \( \gamma-\delta \) coordinate system. A high-frequency current injected into the \( \gamma-\delta \) axes is expressed in Eq. (2).
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Fig. 1. Block diagram of sensorless drive system

\[\begin{bmatrix} i_{rh} \\ i_{ld} \end{bmatrix} = I_h \begin{bmatrix} \sin \theta_h \\ 0 \end{bmatrix} \quad \text{(2)}\]

where \(I_h\) is the amplitude of the high frequency current. \(\theta_h = \omega_f t\) is the phase angle of the high-frequency current.

As a result, a high-frequency voltage represented by Eq. (3) in the \(\gamma-\delta\) axes is generated.

\[
\begin{bmatrix} v_{\gamma h} \\ v_{\delta h} \end{bmatrix} = R L_h \begin{bmatrix} \sin \theta_h \\ 0 \end{bmatrix} + \frac{L_0 I_h}{2} \left[ (\omega_f + \omega_{est}) \left( \cos \theta_h + (\omega_f - \omega_{est}) \cos \theta_h \right) \right] + \frac{L_1 I_h}{2} \left[ (\omega_f - 2 \omega + \omega_{est}) \left( \frac{\cos(-\theta_h - 2\Delta \theta)}{\sin(-\theta_h - 2\Delta \theta)} \right) + (\omega_f + 2 \omega - \omega_{est}) \left( \frac{\cos(\theta_h - 2\Delta \theta)}{\sin(\theta_h - 2\Delta \theta)} \right) \right] + \omega_f \left[ \frac{\sin(\Delta \theta)}{\cos(\Delta \theta)} \right] \quad \text{(3)}
\]

where \(L_0 = (L_d + L_q)/2, L_1 = (L_d - L_q)/2,\) and \(\Delta \theta\) is the magnetic pole position error.

Assuming that \(\Delta \theta\) is small enough, \(\omega_f \cos(\Delta \theta)\) of Eq. (3) can be considered a DC component that is removed by using a BPF with a center frequency of \(\omega_f\). Then, \(v_{\delta h}\) multiplied by \(\cos \theta_h\) is given by Eq. (4):

\[
v_{\delta h} \times \cos \theta_h = \frac{L_0 \omega_{est} I_h}{2} \sin(2\theta_h) - \frac{L_1 I_h (\omega_f - 2\omega + \omega_{est})}{4} \sin(2\Delta \theta) + \frac{L_1 I_h (\omega_f + 2\omega - \omega_{est})}{4} \sin(2\theta_h - 2\Delta \theta) - \sin(2\Delta \theta) \quad \text{(4)}
\]

Eq. (4) includes the position error \(\Delta \theta\). The magnetic pole position can be estimated by the average of one cycle of Eq. (4).

Figures 1, 2 and 3 show the block diagram of sensorless drive system. Ratings and parameters of the IPMSM and the controller are listed in Table 1.

Table 1. Ratings and Parameters of IPMSM and Controller

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power [W]</td>
<td>1500</td>
</tr>
<tr>
<td>Rated voltage [V]</td>
<td>180</td>
</tr>
<tr>
<td>Rated current [A]</td>
<td>6.1</td>
</tr>
<tr>
<td>Rated speed [min⁻¹]</td>
<td>1800</td>
</tr>
<tr>
<td>Rated torque [N·m]</td>
<td>7.9</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>3</td>
</tr>
<tr>
<td>Stator resistance R [Ω]</td>
<td>0.785</td>
</tr>
<tr>
<td>d-axis inductance Ld [mH]</td>
<td>9.77</td>
</tr>
<tr>
<td>q-axis inductance Lq [mH]</td>
<td>22.4</td>
</tr>
<tr>
<td>Rotor magnet flux (\Phi) [Wh]</td>
<td>0.2605</td>
</tr>
<tr>
<td>Rotor inertia I [kg·m²]</td>
<td>0.00144</td>
</tr>
<tr>
<td>Injection current frequency [Hz]</td>
<td>500</td>
</tr>
<tr>
<td>The speed controller bandwidth [rad/s]</td>
<td>19</td>
</tr>
<tr>
<td>The current controller bandwidth [rad/s]</td>
<td>1500</td>
</tr>
</tbody>
</table>

3. Audible Noise by High-frequency Current

During high-frequency signal injection, the problem of audible noise arises. We measured the audible noise of the tested machine at steady states. The measured values of audible noise are listed in Table 2.

Table 2 shows the relationship between audible noise and high-frequency current amplitude. It can be confirmed that the audible noise is reduced by decreasing the current amplitude. However, with decreasing amplitude, the precision of position estimation deteriorates. When the precision of position estimation deteriorates too much, the audible noise is increased. In addition, when the current amplitude is decreased too much, it is impossible to control the IPMSM in the transient state. The optimal current amplitude depends on conditions such as rotational speed.

Therefore, it is necessary to control the high-frequency current amplitude command value to reduce the audible noise. At the steady state, the high-frequency current amplitude should be small as well as at the transient state, the amplitude should be high.
4. Audible Noise Reduction Method Based on Optimization of High-frequency Current Amplitude

As described in the previous section, it is necessary to control the high-frequency current amplitude command value in order to reduce the audible noise. In general, the high-frequency current amplitude is maintained at a required constant value in the transient state. The injection current amplitude command about 2.5 A is necessary for the motor drive using the general approach to stabilize in the transient state and the low speed range. This general approach results in a large audible noise.

Here, to reduce the audible noise due to the high-frequency current, we propose a method for minimizing the injection signal to a level suitable for the driving state without providing the lower limit setting of the high-frequency current amplitude command value. We show the outline of the proposed method in Fig. 4. And the high-frequency current amplitude command value is determined as shown in Fig. 5.

We now proceed to explain the principle of the proposed method. Speed error $\omega_{err}$ can be expressed as in Eq. (5).

$$\omega_{err} = \omega_{ref} - \omega_{est}$$

where $\omega_{ref}$ is the speed command, and $\omega_{est}$ is the estimated speed.

The value of $\omega_{err}$ is low in the steady state, and at the transient state it is high. When the high-frequency current amplitude is reduced, the value of $\omega_{err}$ is increased because the estimation accuracy deteriorates. Therefore, the value of $\omega_{err}$ can distinguish the state. Our proposed method uses the threshold values $\omega_{err}$, C1, C3, and C5 to distinguish the steady and transient states. The high-frequency current amplitude command value is then determined. The threshold values C1, C3, and C5 are determined by experiments explained in Sect. 5. In the proposed method, the average value of the absolute value of $\omega_{err}$ is used for determining the optimal current amplitude command value because $\omega_{err}$ fluctuates.

In addition, C2, C4, and C6 are not necessary to be determined exactly. However, C2 should be large, because the large injection current is necessary to stabilize in the transient state. And, C4 should be small to decide exactly the converged value of injection current amplitude command.

### Table 2. Relationship between high-frequency current amplitude and audible noise

<table>
<thead>
<tr>
<th>Speed</th>
<th>90 min$^{-1}$</th>
<th>30 min$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load torque</td>
<td>0.0Nm</td>
<td>0.0Nm</td>
</tr>
<tr>
<td>With sense, No current injection</td>
<td>41.4</td>
<td>44.1</td>
</tr>
<tr>
<td>0.05A</td>
<td>Loss of control</td>
<td>Loss of control</td>
</tr>
<tr>
<td>0.1A</td>
<td>42.6</td>
<td>Loss of control</td>
</tr>
<tr>
<td>0.2A</td>
<td>41.9</td>
<td>48.4</td>
</tr>
<tr>
<td>0.4A</td>
<td>42.3</td>
<td>49.9</td>
</tr>
<tr>
<td>0.8A</td>
<td>42.8</td>
<td>52.1</td>
</tr>
<tr>
<td>1.0A</td>
<td>43</td>
<td>53.7</td>
</tr>
<tr>
<td>1.2A</td>
<td>45.2</td>
<td>55.7</td>
</tr>
<tr>
<td>2.5A</td>
<td>53.8</td>
<td>61.3</td>
</tr>
</tbody>
</table>

### Fig. 4. Method proposed for minimizing the injection signal level suitable for IPMSM driving states

C1: Load distinction threshold
C2: Increase current Gain
C3: Stability criterion threshold
C4: Decrease current Gain
C5: Instability distinction threshold
C6: Increase current Gain

5. Method for Determining the Threshold

In this section, we explain how to determine the three threshold values C1, C3, and C5. It is necessary to carry out two tests.

5.1 Method for Deciding C1 and C3

We changed the load torque slowly at a constant speed to decide C1 and C3. The rate of change of the load torque is selected to a small value so that the position estimation is not deteriorated. For the position estimation, the condition is considered as steady state. To emphasise this condition, the injection current was set at small value, 0.5 A. It should be noticed that the injection current is not necessary to be so small, because the speed error is depending on only the speed controller characteristics under the slow rate of change the load torque. If the
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5.2 Method for Deciding C5

When the high-frequency current amplitude command value was reduced as shown in Fig. 7, we measured the average value of the absolute value of $\omega_{err}$. The experiment was performed at 90 min$^{-1}$ (5% of the rated speed) under no-load condition. (Fig. 8)

Figure 8 shows that the average of the absolute value of the speed error is increased, when the high-frequency current amplitude command value is reduced. From the value of the average of the absolute value of the speed error, we can distinguish the position estimate stability or instability.

The threshold value $C_5$ is determined by the permissible range of the position error. $C_5$ is the average value of the absolute value of the speed error when the position error exceeds the permissible range the first time. This time, the permissible range of the position error was set at $20^\circ$. Then, the value of $C_5$ is decided at 2.0. We determined $C_1$, $C_3$, and $C_5$ by the experiment.

6. Experimental Results

In this section, we demonstrate the effectiveness of the proposed method by explaining experimental results. We conducted the experiment under the condition with the motor speed at 90 min$^{-1}$ with no-load. The optimum high-frequency current amplitude command value was decided by our proposed method. After the current amplitude was decided, we changed the motor speed to 30 min$^{-1}$ (Fig. 9).

To verify the effectiveness of the proposed method at other speeds, we carried out the experiment between 60 min$^{-1}$ and 180 min$^{-1}$ (Fig. 10). Figure 9 and Fig. 10 show that the high-frequency current amplitude command value is decided over the entire permissible range. Figure 9 and Table 2 show that audible noise is greatly reduced by this approach. The results of the experiments in which the load is changed slowly and quickly are presented in Fig. 11 and Fig. 12, respectively. These figures show that the proposed method is effective under the rated load condition. Converged values of injection current amplitude command are slightly different between Fig. 11 and Fig. 12 despite that the value of q-axis current is
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- Fig. 9. Experimental results of the proposed method (Speed varies from 90 min⁻¹ to 30 min⁻¹)
  - (a) High-frequency current amplitude command value
  - (b) Speed command
  - (c) Position error
  - (d) Average value of the absolute value of the speed error

- Fig. 10. Experimental results of the proposed method (Speed varies from 180 min⁻¹ to 60 min⁻¹)
  - (a) High-frequency current amplitude command value
  - (b) Speed command
  - (c) Position error

- Fig. 11. Experimental results of the proposed method (90 min⁻¹, Load torque changes slowly from 0 Nm to 7.9 Nm.)
  - (a) High-frequency current amplitude command value
  - (b) iq
  - (c) Position error

almost same (10 A). Even if values of q-axis current and injection current amplitude command are almost same, values of speed error and position error are slightly different, because values of speed error and position error fluctuate. So, converged values of injection current amplitude command are not always the same. The oscillation of values of speed error and position error under the condition at the large load torque is wider than that at no-load. Our many experiments confirmed that the injection current amplitude command converges between 0.7 A and 1.2 A under the condition with the motor speed at 90 min⁻¹ with load torque 7.9 Nm. Figure 13 shows experimental results, when the permissible range of the position is set at 10°. We carried out the experiment between 30 min⁻¹ and 90 min⁻¹ with the value of C5 set at 0.95. Figure 13 shows that the position error is smaller than the permissible range of the position error. Table 3 shows the comparison of audible noise obtained by experimental results in the conventional method and the proposed method. We confirmed that the injection current amplitude command converges between 2.0 A and 2.3 A under the condition with the motor speed at 30 min⁻¹ and the value of C5 set at 2.0. Table 3 shows that the audible noise occurred by the proposed method is smaller than that occurred by the conventional method. Experimental results show that the proposed method is effective for reducing the audible noise.
7. Conclusion

In this paper, we propose an audible noise reduction method using the speed error for sensorless IPMSM drives based on high-frequency current injection. The experimental results demonstrated the effectiveness of the proposed method. The threshold value $C_5$ is determined by the permissible range of the position error. By determining the threshold value of the speed error, the high-frequency current amplitude command value is minimized depending on operating conditions.

### References


### Appendix

#### Symbols

$V_d, V_q$: d and q axes voltages, respectively (V)
$I_d, I_q$: d and q axes currents, respectively (A)
$L_d, L_q$: d and q axes inductances, respectively (H)
$R$: Stator resistance ($\Omega$)
$\omega$: Actual rotor speed (rad/s)
$\omega_{est}$: Estimated speed (rad/s)
$\omega_{ref}$: Speed command (rad/s)
$\psi$: Frequency of the injection current (rad/s)
$\psi$: Flux linkage (Wh)

<table>
<thead>
<tr>
<th>Table 3. The comparison of audible noise in the conventional method and the proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Load torque</td>
</tr>
<tr>
<td>The proposed method</td>
</tr>
<tr>
<td>(The conventional method with current injection 2.5A)</td>
</tr>
</tbody>
</table>

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Audible Noise Reduction Method in IPMSM Sensorless Control (Yuki Tauchi et al.)
Yuki Tauchi (Student Member) was born in 1990 in Shizuoka, Japan. He received the B.E. degree from Meiji University in 2013. He is currently working towards the M.E. degree in the same university. His research interests are in motor drives.

Hisao Kubota (Senior Member) received the B.E., M.E., and Ph.D. degrees in electrical engineering from Meiji University, Japan, in 1982, 1984, and 1989, respectively. Since 1984, he has been a member of the faculty at Meiji University, where he is currently a Professor. His research interests are in motor drives. Dr. Kubota is a member of the Institute of Electrical Engineers of Japan. He is also a member of the IEEE Industry Applications, Industrial Electronics, and Power Electronics Societies.