Sensorless Control of a Novel IPMSM Based on High-Frequency Injection

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Keywords

<<Permanent magnet motor>>, <<Synchronous motor>>, <<Self-sensing control>>, <<Energy efficiency>>, <<Test bench>>

Abstract

Due to the challenge for sensorless control of concentrated windings (CW) interior permanent magnet synchronous machines (IPMSMs), this paper presents the analysis of a novel stator IPMSM for sensorless control based on high-frequency rotating voltage signal injection method. The topology of the machine is introduced and the new IPMSM has the advantage of less space harmonics. The sensorless control scheme is developed, and the cross saturation is taken into account to improve the accuracy of position estimation. To support this, the high-frequency inductances of the machine are analyzed by finite-element analysis (FEA) method. Both of the steady and dynamic state experimental results verify the effectiveness of the drive system.

Introduction

Interior permanent magnet synchronous machines (IPMSMs) have highlight due to the structure saliency especially for the sensorless control based on high-frequency (HF) injection method. IPMSMs using concentrated windings (CW) offer the advantages of short and less complex end-winding, high slot filling factor, low coggging torque, greater fault tolerance, and low manufacturing costs. The stator coils may be wound either on all the teeth (double-layer winding) or only on alternate teeth (single-layer winding) and the manufacturing of these windings may be much cheaper because they contains simple coils that can be wounded automatically than distributed windings (DW). However, CW IPMSMs also have more space harmonics. The novel IPMSM [1-2] used in the paper has new stator structure can decrease the disadvantage which can be seen in Fig.1 and Fig.2.

Concerning sensorless control strategies, back electromotive force (back EMF) estimation-based methods have been analyzed and developed in order to determine the rotor position and speed of PMSM without position sensors [3-6]. However, since the amplitude of back EMF is proportional to the rotor
speed, it fails in the low-speed region. The small or zero back-EMF voltage will have serious effects on the accuracy of the estimated rotor position. Further researchers have found that the machine anisotropic properties provide additional information on the field angle or the position of the rotor. This inherent property makes it possible to use transient excitations by injecting signals with other frequencies than the fundamental [7-10]. High-frequency (HF) injection sensorless control method shows good rotor position estimation results at low speed even or zero speed.

Of course, the magnetic and mechanical design of the synchronous machines has impact on the performance of sensorless control with HF injection. The standard design of servo motors with distributed windings (DW) is extremely qualified to be controlled without an encoder. Unfortunately modern designs of synchronous machines especially when not based on the fundamental wave inside do not support sensorless control very well. This indicates more research to be done to investigate in sensorless control of these new designs [11]. Sensorless control of CW IPMSMs is still a challenge. The magnetic field of these CW has more space harmonics, including sub-harmonics, which lead to undesirable effects. In this paper, the novel IPMSM was used for sensorless control based on HF injection method, and the experiment results show the good performance. It proved the new IPMSM has the advantage of less space harmonics. The cross saturation of the IPMSM is also taken into account. When using the decoupling method, the error of the rotor position estimation will be decreased.

Model of the novel IPMSM

The novel machine is a 12-teeth/10-poles concentrated winding interior permanent magnet synchronous machine (IPMSM). Its prototype is shown in Fig.1. The new stator structure of the IPMSM is using different slot depth, and the coil-sides in the corresponding slots can be shift away from the slot-opening region to reduce proximity effect in the winding conductors which is presently mostly near the slot opening [1].

![Figure 1: Cross section of the IPMSM](image1)

![Figure 2: Power losses of the IPMSM](image2)

Due to its special double-layer concentrated winding and notable topology, the IPMSM has the following advantages:

- Low cost (simple manufacturing)
- High efficiency (e.g. short end winding, low copper loss, low cogging torque and low torque ripple) see Fig.2
- High energy density (compact design)

The stator flux linkage vector equation of IPMSM can be expressed as

$$\psi_s = L_s i_s + \psi_f$$  \hspace{1cm} (1)

Subscript $s$ denotes the stationary reference frame. The stator voltage vector equation can be expressed as

$$u_s = R_s i_s + \frac{d\psi_s}{dt}$$  \hspace{1cm} (2)

Sensorless Control of the IPMSM

A high frequency component is superposed to the current control output signal resulting in a high frequency current response, which can be used for detecting the orientation of the rotor. The position dependent high frequency currents can be measured with the standard current sensors available in industrial drives anyway. There is no need for any a additional hardware being not available in standard industrial drives.
High-frequency injection method

High-frequency injection of PMSM sensorless control is based on the magnetic saliency phenomenon. In this method, a high frequency voltage or current vector signal is superimposed on machine fundamental excitation. The corresponding high frequency current signal contains rotor position information, and is analyzed to track spatial saliencies and to estimate the rotor or flux position.

The sensorless control scheme of the IPMSM with high-frequency rotating voltage signal injection is shown in Fig.3.

If inject three-phase high frequency sine voltage signal to the PMSM, rotating space voltage vector with constant amplitude and high speed in the machine will be achieved. The injection voltage can be described as

\[ u_s^c = |u_c| e^{j \omega_c t} \]

Where \( \omega_c \) is the frequency, and \( |u_c| \) is the amplitude of the injected rotating voltage vector. Subscript \( c \) means the injected (carrier) signals. The voltage vector \( u_s^c \) can be transformed to the rotational \( d-q \) reference frame.

\[ u_{dq}^c = \frac{L^{dq}}{L^{dq}} \frac{d i_{dq}^c}{dt} \]

Where

\[ L^{dq} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \]

The stator voltage vector in the rotational \( d-q \) reference frame is known as

\[ u_{dq} = |u_s| e^{j \omega_s t} e^{-j \omega_r t} = |u_s| e^{j (\omega_s - \omega_r) t} \]

The superimposed stator current vector \( i_s^c \) can be calculated from the equation above

\[ i_s^c = |i_p| e^{j \omega_s t} + |i_a| e^{j (\omega_s t + 2 \omega_r t)} \]
Where
\[ \Sigma L = 1/2(L_d + L_q) \quad \Delta L = 1/2(L_q - L_d) \] (8)

\[ |i_p| = \frac{\Sigma L}{\Sigma L^2 - \Delta L^2} - j|u_c|/\omega_c \] (9)

\[ |i_n| = \frac{\Delta L}{\Sigma L^2 - \Delta L^2} - j|u_c|/\omega_c \] (10)

Equation (7) describes that the superimposed stator current vector can be departed into two components: one vector \( i_p \) is rotating in positive direction according to the injection angular speed \( \omega_c \); the other one vector \( i_n \) is rotating in negative direction according to the angular speed \( \omega_c + 2\omega_r \), and the rotational speed information \( \omega_r \) only is included in the vector \( i_n \).

In order to get the estimated rotor position information, at first use (7) to multiply \( e^{j\omega_c t} \)

\[ i_s^* \times e^{j\omega_c t} = |i_p|e^{j2\omega_c t} + |i_n|e^{2\omega_r t} \] (11)

The first step of sensorless control method in Fig.3 uses only the second term on the right-hand side of (7), because only this part includes the speed information.

The second step is using a low-pass filter (LPF) in order to extract \( \omega_r \) from the high frequency current signals.

The third step is using the phase-locked loop (PLL) block to estimate the speed and the rotor position information.

**Analysis of the inductances of the IPMSM**

It is important to point out that the inductance \( L_d \) and \( L_q \) of the IPMSM is changed with the high-frequency injection, and even the saturation is also changed with injection. Cross-saturation is resulting from the cross coupling between \( d \) and \( q \)-axis, and the mutual inductance \( L_{dq} \) need to be measured. Under the saturation effect, the \( L_d \), \( L_q \) and \( L_{dq} \) inductances depend non-linearly on the stator currents and load angle.

When the cross coupling between \( d \) and \( q \)-axis is considered in the IPMSM, it is also can be said the mutual inductance \( L_{dq} = L_{qd} \) is considered. (6) is changed like this

\[ L_{dq} = \begin{bmatrix} L_d & L_{dq} \\ L_{qd} & L_q \end{bmatrix} \] (12)

Based on 2-D finite element method (FEM), the characteristics of non-linear machine parameters are investigated and analyzed. The fixed \( d \) and \( q \)-axis stator current sources are used to excite the FEM model of the IPMSM, then the HF current signals are injected into the three phases of the stator separately. Using transient solution type, the total self-inductance and mutual inductance can be achieved at each simulation point. Fig.4 and Fig.5 show the results of inductances based on different \( d \) and \( q \)-axis stator currents.

**Figure 4:** The inductance \( L_d \) without HF

**Figure 5:** The inductance \( L_q \) without HF
Fig. 6 shows the stator current impedance characteristics of the IPMSM obtained by FE simulations under various stator current of $d$-axis. The magnitude of the $d$-axis current has been set to 10, 50, 100 and 200 A without the HF signal injection, the inductance value $L_q - L_d$ is changing with the current and rotor position. Fig. 7 shows the mutual inductance $L_{dq}$ changing with the current and rotor position.

Fig. 8 shows the high-frequency (HF) current injection impedance characteristics of the IPMSM obtained by FE (finite-element) simulations under various HF currents, and the fundamental stator current is set as 50 A. The magnitude of the HF current has been set to 2, 4, 6 and 8 A, and the rotating currents are injected directly to the stator of the IPMSM. The inductance value $L_q - L_d$ is changing with the current and rotor position. Fig. 9 shows the mutual inductance $L_{dq}$ changing with the current and rotor position.

The voltage vector $u_c^s$ will get the rotating flux field in the IPMSM, and the speed $\omega_c$ is much higher than $\omega_r$, the speed of the rotating rotor. The flux field will be modulated by the saliency of the rotor, and the results of modulation will be seen from the current. If the cross coupling is considered, the current which is changed with the rotating high-frequency voltage signal injection can be described as

$$i^s = |i_p|e^{j\omega_ct} + |i_n|e^{j(\omega_c t + 2\omega_r t + \Phi)}$$

(13)

Where

$$\Phi = \sin^{-1}(\frac{L_{dq}}{\Delta L})$$

(14)

$$|i_p| = \frac{\Sigma L}{\Sigma L^2 - \Delta L^2 - L_{dq}^2} \frac{-j|u_c|}{\omega_c}$$

(15)

$$|i_n| = \frac{\Delta L}{\Sigma L^2 - \Delta L^2 - L_{dq}^2} \frac{-j|u_c|}{\omega_c}$$

(16)

Fig. 10 shows the cross-saturation effects of the IPMSM calculated using (14), and the mutual inductance and the value $L_q - L_d$ are obtained by FE simulations under various HF currents, and the fundamental stator current is set as 50 A.
Figure 10: The cross-saturation effects with HF

Table I: Technical data of the IPMSM

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed</td>
<td>1800r/min</td>
</tr>
<tr>
<td>Rated torque</td>
<td>2Nm</td>
</tr>
<tr>
<td>Rated current</td>
<td>50A</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>8.5A</td>
</tr>
<tr>
<td>Pole pair</td>
<td>5</td>
</tr>
<tr>
<td>d/q-axis inductance</td>
<td>0.05/0.095mH</td>
</tr>
</tbody>
</table>

Experimental Results

The parameters of IPMSM are shown in Table I. A carrier voltage $u_c$ was injected with a rotating high frequency $f_c$ of 1 kHz and an amplitude of 2V. The resulting high frequency current $i_c$ obtained an amplitude of 10A. The experimental results present here with the IPMSM running under the mechanical load of half rated torque.

Based on the analysis of the inductance characteristics of the IPMSM, experiments on sensorless operation have been performed using the control scheme of Fig.3. The test bench of the IPMSM can be seen in Fig.11. Because the IPMSM have the advantage of low cost, the LC motor is referred to the novel IPMSM.

During the experiments, the speed of the LC motor is very low from 0 rpm to 60 rpm in Fig.12, and the estimated position can follow the actual position which can be got from the rotor position encode. In Fig.13, when the speed suddenly changes from positive 120 rpm to negative -120 rpm, the estimated position can also follow the actual position.
Conclusions

For the novel IPMSM, the high-frequency injection method has not been presented before. In this paper the high-frequency rotating voltage signal injection method was presented. The experimental results of the position estimation show the satisfactory performance of this method at low speed and the correct inductances analysis of the machine. Based on the application of the machine and sensorless control strategy, the system cost realizes the maximum reduction. Both of the steady state and dynamic state experimental results verify the effectiveness of the drive system.

References
