A study on IPMSM Design for Sensorless control with High-Frequency Voltage Signal Injection

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***Abstract*—This paper proposes concept of motor for sensorless control and proper inductance distribution of Interior Permanent Magnet Synchronous Motor (IPMSM) for sensorless-oriented design based on the high-frequency voltage signal injection. There are two methods in the sensorless position control of IPMSM according to the operating speed. At low speed or standstill, rotor position is estimated from the inductance distribution determined by saliency of the magnetic path. And rotor position can be estimated easier as this inductance distribution is sinusoidal. However, in the motor design part, it is difficult to make the sinusoidal inductance distribution because the inductance profile is distorted by means of core saturation with input current under the load condition. In order to find a solution to this problem, it is established cause of the estimating position error, and concept of IPMSM for sensorless-oriented design is proposed. In this concept, as the Total Harmonic Distortion of the phase inductance in specific load condition is decreased, the rotor position is better estimated. The inductance distribution based on the high-frequency voltage signal injection is compared with test results. Both simulation error patterns and experiments are presented to verify the validity of the established method.**

***Index Terms*—AC machine, inductance, motor drives, sensorless control**

I. INTRODUCTION

Today Interior Permanent Magnet Synchronous Motor (IPMSM) is usually used for EV/HEV traction because of its high torque density. Fulfilling the best performance of the machine, position sensor is essentially needed for machine vector control. As the result, an encoder or resolver has been attached to the shaft of the rotor. These sensors make many problems with increasing system cost, volume and complexity, or decreasing reliability [1]. For these reasons, nowadays, design method of IPMSM for sensorless drive and sensorless control techniques are getting important.

There are several methods in the sensorless position control of IPMSM according to the operating speed. At low speed or standstill, rotor position is estimated from the inductance distribution determined by saliency of the magnetic path [2]. With high-frequency signal injection method, the position of rotor could be estimated based on the saliency [3]. However, it is not easy to estimate rotor position actually, since inductance profile is distorted by means of core saturation with input current under the load condition.

In this paper, it is proposed design concept of IPMSM for sensorless-oriented design based on the high-frequency voltage signal injection. Consequently the inductance distribution based on the high-frequency voltage injection is compared with test results.

II. CAUSE OF INDUCTANCE ESTIMATION ERROR IN IPMSM FOR SENSORLESS CONTROL

A. Basic Principle of High-frequency Rotating Voltage Signal Injection Method [1]

Under the assumption that the high-frequency voltage signal is injected into the IPMSM and the rotating speed is almost zero, the voltage drop of the resistance and the back EMF can be ignored. Then, the voltage equation of IPMSM in the rotor *d-/q*-axis reference frame is described as

$$\begin{bmatrix} v_{dsh}^{r} \\ v_{qsh}^{r} \end{bmatrix} = \begin{bmatrix} L_{ds} & 0 \\ 0 & Lqs \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{dsh}^{r} \\ i_{qsh}^{r} \end{bmatrix} \tag{1}$$

According to the injected voltage signal, the current response can be derived from (1) as

$$\begin{bmatrix} i_{dsh}^{r} \\ i_{qsh}^{r} \end{bmatrix} = \int \begin{bmatrix} L_{ds} & 0 \\ 0 & Lqs \end{bmatrix}^{-1} \frac{d}{dt} \begin{bmatrix} v_{dsh}^{r} \\ v_{qsh}^{r} \end{bmatrix} dt \tag{2}$$

where $[v^{r}_{dsh}, v^{r}_{qsh}]^{T}$ and $[i^{r}_{dsh}, i^{r}_{qsh}]^{T}$ are the injected high-frequency voltage vector and the corresponding current vector in the synchronous rotor reference frame, respectively. The inductance matrix is represented in terms of the *d-/q*-axis inductance, L_{ds}, L_{qs}, in the synchronous rotor reference frame. From the current response, (2), the rotor position information can be extracted through a kind of signal processing.

B. Cause of the estimating position error for Sensorless control in IPMSM

In some IPMSMs, such as the machine with high power density and speed range, the variation of the inductance according to the rotor position is not sinusoidal because of flux saturation by input current under the load condition [5]. If the phase inductance has the *n-th* space harmonic inductance, the harmonic inductance matrix, L_{abch} is expressed as

$$L_{abch} = L_h \begin{bmatrix} \cos 2\theta_r n & \cos 2n\left(\theta_r - \frac{\pi}{3}\right) & \cos 2n\left(\theta_r + \frac{\pi}{3}\right) \\ \cos 2n\left(\theta_r - \frac{\pi}{3}\right) & \cos 2n\left(\theta_r + \frac{\pi}{3}\right) & \cos 2\theta_r n \\ \cos 2n\left(\theta_r + \frac{\pi}{3}\right) & \cos 2\theta_r n & \cos 2n\left(\theta_r - \frac{\pi}{3}\right) \end{bmatrix} \tag{3}$$

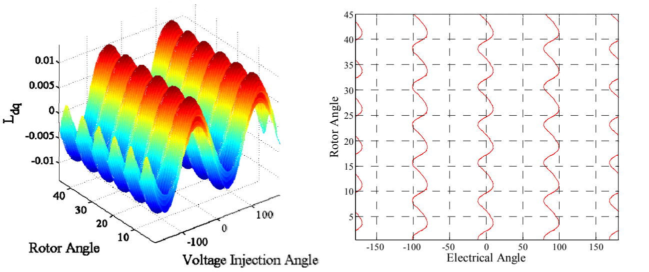

Fig. 1. Variation of the inductance according to the rotor position and current

where L_h is the amplitude of the harmonic inductance, and θ_r is the rotor position. In addition, the harmonic inductance matrix, L_{sh}, is represented in the synchronous rotor reference frame as

$$L_{sh}=\frac{3}{2}L_{mh}\begin{bmatrix}\cos 6\theta_r m & -\sin 6\theta_r m\\ -\sin 6\theta_r m & -\cos 6\theta_r m\end{bmatrix} \quad @\,n=3m-1$$
$$L_{sh}=\frac{3}{2}L_{mh}\begin{bmatrix}\cos 6\theta_r m & \sin 6\theta_r m\\ \sin 6\theta_r m & -\cos 6\theta_r m\end{bmatrix} \quad @\,n=3m+1 \qquad (4)$$

where L_{mh} is the amplitude of the *n-th* harmonic inductance.

The harmonic orders of the inductance as shown in Table I. The *6n-th* harmonics of the inductance, L_{sh}, in the synchronous rotor reference frame is calculated by any *n-th* phase harmonic inductance according to the rotor position. This *6n-th* harmonics of the inductance, L_{sh}, cause the estimating error on the current response. If the phase inductance has the *n-th* space harmonic inductance, the corresponding current response can be deduced as

$$\begin{bmatrix} i^s_{dsh}\\ i^s_{qsh}\end{bmatrix}=\gamma\begin{bmatrix}\frac{\alpha}{\gamma}\cos\theta_r+\frac{\beta}{\gamma}\sin\theta_r\\ \frac{\alpha}{\gamma}\sin\theta_r-\frac{\beta}{\gamma}\cos\theta_r\end{bmatrix}\sin\omega_h t \qquad (5)$$
$$=\gamma\begin{bmatrix}\cos(\theta_r-\rho)\\ \sin(\theta_r-\rho)\end{bmatrix}\sin\omega_h t \qquad \rho=\tan^{-1}\frac{\beta}{\alpha}$$
$$\alpha=A\frac{V_{inj}}{\omega_h}\left(L_{qsf}+L_{qsh}\right) \qquad \beta=A\frac{V_{inj}}{\omega_h}L^r_{qdsh}$$
$$A=\frac{1}{\left(L_{dsf}+L_{dsh}\right)\left(L_{qsf}+L_{qsh}\right)-L^r_{dqsh}L^r_{qdsh}}$$
$$\gamma=\sqrt{\alpha^2+\beta^2}$$

where V_{inj} is the amplitude of signal injection voltage, L_{sdf}, L_{qsf} are the *d-/q-axis* inductance of fundamental, L_{dsh}, L_{qsh} are the *d-/q-axis* inductance of harmonic.

There are errors, ρ, estimated 6-th harmonic, and it presented as

$$\rho=\tan^{-1}\frac{\beta}{\alpha}\approx\tan^{-1}\frac{-L_{mh}\sin 6\theta_r m}{L^r_{qsf}} \quad @\,n=3m-1$$
$$\rho=\tan^{-1}\frac{\beta}{\alpha}\approx\tan^{-1}\frac{L_{mh}\sin 6\theta_r m}{L^r_{qsf}} \quad @\,n=3m+1 \qquad (6)$$

TABLE I
HARMONICS ORDER OF L_{abch} AND L_{sh}

n	2	4	5	7	8	10	11	13	14	…
m	1	1	2	2	3	3	4	4	5	…
L_{sh}	6	6	12	12	18	18	24	24	30	…

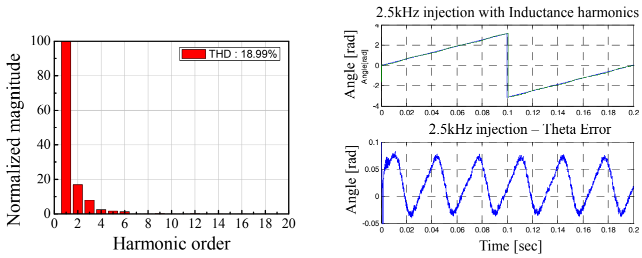

Fig. 2. THD of phase inductance and current ripple

III. Concept of IPMSM for Sensorless-Oriented Design

Total Harmonic Distortion (THD) of phase inductance and current ripple is presented in Fig.2. As the THD of the phase inductance in specific load condition is decreased, the rotor position is better estimated. Thus, the best way to design IPMSM is reducing THD of phase inductance under the all load condition. There are several methods in the design part of IPMSM for reducing THD of phase inductance. One is based on magnetical loading, and the other considers the pole/slot combination of an IPMSM. In the first group, to reduce the THD of phase inductance, the large magnetical loading expressed the flux of permanent magnet is used because it has not effect on the harmonic by the input current under the load condition. In second group, the THD of the phase inductance is reduced from the distributed winding type: the spatial core saturation is relieved by structural magnetic path of the distributed winding type compared with those of the concentrated winding type. These kinds of design concept are entered into details in full paper.

IV. Results

This paper proposes concept of motor for sensorless control and proper inductance distribution of IPMSM for sensorless-oriented design based on the high-frequency voltage signal injection. In order to reduce the rotor position error, it is established cause of the estimating position error. As the THD of the phase inductance in specific load condition is decreased, the rotor position is better estimated.

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