전압주입 방식을 이용한 PMSM 센서리스 제어에 관한 연구

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Sensorless control of PMSM in low speed range using high frequency voltage injection

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ABSTRACT

This paper describes the sensorless technique for the surface-mounted permanent-magent synchronous motor(SPMSM or PMSM) drive based on magnetic saliency. The control technique is a sensorless control algorithm that injects the high frequency voltage to the stator terminal in order to estimate the rotor position and speed. The rotor position and speed for sensorless vector control is achieved by appropriate signal processing to extract the position information from the stator current in the low speed range including zero speed. Proposed sensorless algorithm using the double-band hysteresis controller and initial rotor position detection exhibits excellent reference tracking and increased robustness. Experimental results are presented to verify the feasibility of the proposed control schemes.

1. Introduction

Sensorless control of PMSM using signal injection is based on magnetic saliency of the motor, due to saturation effect or geometric construction. There is no lower limit on the rotor velocity for which these techniques can operate, because these methods have no concern with magnitude of back EMF[1][2][3].

This paper describes sensorless control of PMSM in low speed range using high frequency voltage signal injection. When high frequency voltage signal is injected to the motor, the stator core around the magnet poles is saturated. This phenomenon results the magnetic saliency of PMSM that has the information of rotor positon and speed. Proposed sensorless algorithm using the double-band hysteresis control[4] and initial rotor position detection exhibits excellent reference tracking and increased robustness. Also, it does not require the knowledge of any motor parameter, while it allows low cost implementation only requiring current sensors already included in standard drives.

2. High Frequency Model of PMSM

If the frequency of injected voltage is sufficiently high compared to the rotor speed when the machine is running, the motor speed can be considered as zero from point of view of the high frequency component. High frequency component voltage equation can be represented as following:

$$\begin{bmatrix} v^r_{dsi} \\ v^r_{qsi} \end{bmatrix} = \begin{bmatrix} R_s + j\omega_i L_s & 0 \\ 0 & R_s + j\omega_i L_s \end{bmatrix} \begin{bmatrix} i^r_{dsi} \\ i^r_{qsi} \end{bmatrix} \quad (1)$$

where, $v^r_{dsi}, v^r_{qsi}, i^r_{dsi}, i^r_{qsi}$ are high frequency components of the stator voltage and current in the synchronous reference frame, R_s, L_s are the stator resistance, inductance and ω_i is frequency of the injected voltage.

It is possible to observe that at sufficiently high ω_i, $R_s + j\omega_i L_s$ can be reduced to $j\omega_i L_s$

When the magnet poles are aligned with the stator coil, the flux from magnet is large enough to magnetically saturate the stator iron. Such a saliency that q-axis inductance becomes slightly larger than that of d-axis is generally much lower than the inherent saliency of IPMSM, but allows to consider all PMSMs as salient structures.

From mainly the above reasons, (1) can be reduced to (2).

$$\begin{bmatrix} v_{dsi}^r \\ v_{qsi}^r \end{bmatrix} \cong \begin{bmatrix} j\omega_i L_{ds} & 0 \\ 0 & j\omega_i L_{qs} \end{bmatrix} \begin{bmatrix} i_{dsi}^r \\ i_{qsi}^r \end{bmatrix} \tag{2}$$

where, L_{ds}, L_{qs} are the stator d-q axis inductance.

If the rotor position estimation error is defined as θ_{err}, the relation between the stator voltage, current in an actual d-q axis and the stator voltage, current in the estimated d-q axis are given by the following transform matrix.

$$\begin{bmatrix} v_{dsi}^r \\ v_{qsi}^r \end{bmatrix} = \begin{bmatrix} \cos\theta_{err} & -\sin\theta_{err} \\ \sin\theta_{err} & \cos\theta_{err} \end{bmatrix} \begin{bmatrix} \widehat{v_{dsi}^r} \\ \widehat{v_{qsi}^r} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_{dsi}^r \\ i_{qsi}^r \end{bmatrix} = \begin{bmatrix} \cos\theta_{err} & -\sin\theta_{err} \\ \sin\theta_{err} & \cos\theta_{err} \end{bmatrix} \begin{bmatrix} \widehat{i_{dsi}^r} \\ \widehat{i_{qsi}^r} \end{bmatrix} \tag{4}$$

where, $\widehat{v_{ds}^r}$, $\widehat{v_{qs}^r}$, $\widehat{i_{ds}^r}$, $\widehat{i_{qs}^r}$ are the stator voltage and current in the estimated synchronous reference frame.

From (2),(3),(4) the high frequency component of the stator current in the synchronous reference frame can be represented as following.

$$\widehat{i_{dsi}^r} \cong \frac{(j\omega_i L_{qs} + j\omega_i L_{ds}) + (j\omega_i L_{qs} - j\omega_i L_{ds})\cos 2\theta_{err}}{2\omega_i^2 L_{ds} L_{qs}} \widehat{v_{dsi}^r} + \frac{(j\omega_i L_{ds} - j\omega_i L_{q})\sin 2\theta_{err}}{2\omega_i^2 L_{ds} L_{qs}} \widehat{v_{qsi}^r} \tag{5}$$

$$\widehat{i_{qsi}^r} \cong \frac{(j\omega_i L_{ds} - j\omega_i L_{qs})\sin 2\theta_{err}}{2\omega_i^2 L_{ds} L_{qs}} \widehat{v_{dsi}^r} + \frac{(j\omega_i L_{ds} + j\omega_i L_{qs}) + (j\omega_i L_{ds} - j\omega_i L_{qs})\sin 2\theta_{err}}{2\omega_i^2 L_{ds} L_{qs}} \widehat{v_{qsi}^r} \tag{6}$$

3. Pre-Processor

Pre-processor carries out to extract θ_{err} from the high frequency component of the stator q-axis current in the estimated synchronous reference frame. Fig. 1 shows the block diagram of pre-processor[2].

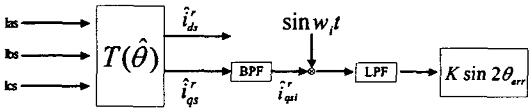


Fig. 1 Block diagram of pre-processor

If the high frequency voltage is injected as in (7), the high frequency component of the stator current in the estimaed synchronous reference frame can be represented as (8), (9).

$$\begin{bmatrix} \widehat{v_{dsi}^r} \\ \widehat{v_{qsi}^r} \end{bmatrix} = v_{si} \begin{bmatrix} \cos(\omega_i t) \\ 0 \end{bmatrix} \tag{7}$$

$$\widehat{i_{dsi}^r} \cong v_{si} \sin \omega_i t \left(\frac{\omega_i L_{qs} + \omega_i L_{ds}}{2\omega_i^2 L_{ds} L_{qs}} + \frac{(\omega_i L_{qs} - \omega_i L_{ds})\cos 2\theta_{err}}{2\omega_i^2 L_{ds} L_{qs}} \right) \tag{8}$$

$$\widehat{i_{qsi}^r} \cong v_{si} \sin \omega_i t \frac{(\omega_i L_{ds} - \omega_i L_{qs})\sin 2\theta_{err}}{2\omega_i^2 L_{ds} L_{qs}} \tag{9}$$

From (9) the input signal to the rotor position estimation error can be obtained via signal process in (10).

$$LPF[\widehat{i_{qsi}^r} \times \sin \omega_i t] \cong \frac{v_{si}(\omega_i L_{ds} - \omega_i L_{qs})}{4\omega_i^2 L_{ds} L_{qs}} \sin 2\theta_{err} \cong K \sin 2\theta_{err} \tag{10}$$

where, $K = \frac{v_{si}(\omega_i L_{ds} - \omega_i L_{qs})}{4\omega_i^2 L_{ds} L_{qs}}$

From the assumption that $\theta_{err} \cong 0$, output of pre-processor in (10) can be reduced to (11).

$$LPF[\widehat{i_{qsi}^r} \times \sin \omega_i t] \cong K 2\theta_{err} \tag{11}$$

4. Sensorless Control Strategy

4.1 Rotor Position Detection at standstill

According to the output of pre-processor, the rotor position estimation error shows an uncertainly $\frac{\pi}{2}$ degree, because of chracteristic of sine function. This problem due to periodicity of sine function mainly have an effect on the starting performance. To overcome this problem, estimation algorithm of the initial rotor position is needed for a relatively smooth start.

Fig. 2 shows the current ellipse in the stationary reference frame at the initial rotor position θ_r. That is, when the balanced high frequency voltage is injected to the stator terminal, the stationary current makes the ellipse due to saturation effect of PMSM.

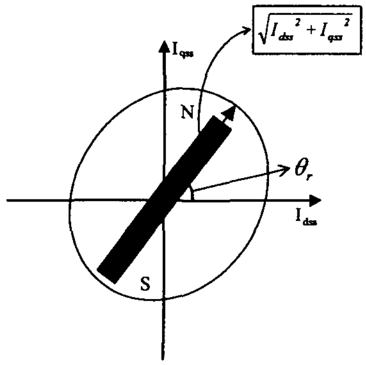


Fig. 2 Current ellipse in the stationary reference frame

The information of the complete one cycle current is needed in order to estimate the rotor position by injecting the high frequency voltage to the stator terminal because the major axis angle of the stator current gives the direct information of the rotor position.

4.2 Double Band Hysteresis Control

Fig. 3 shows process of the double-band five-level hysteresis control. The double-band five-level hysteresis control can be reduced the rotor position estimation error in steady state compared to two-level hysteresis controller. And, the rotor position estimation error can be limited within the inner band. Also, the controller achieves better stability and dynamic performance.

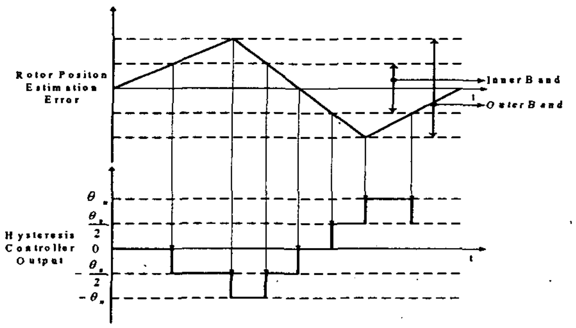


Fig. 3 Double-band 5-Level Hysteresis Control

Fig. 4 shows the block diagram of proposed rotor position and speed estimator.

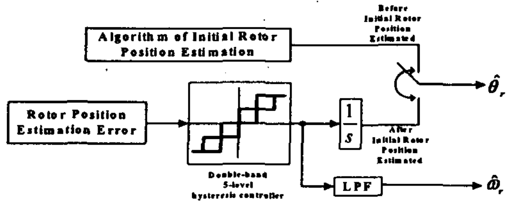


Fig. 4 Block diagram of proposed sensorless control algorithm.

5. Experimental Results

The experiments have performed to verify the proposed sensorless algorithm. A 48 poles rotor, three phase, 2.1KW, 600rpm rated speed, 230V rated voltage, and 9A rated current PMSM was used for the experimental results. Fig. 5 shows the block diagram of the sensorless drive system of PMSM using high frequency voltage injection. Magnitude and frequency of injected voltage is 60V, 355Hz. All programs are implemented in a 32bit floating point DSP TMS320VC33.

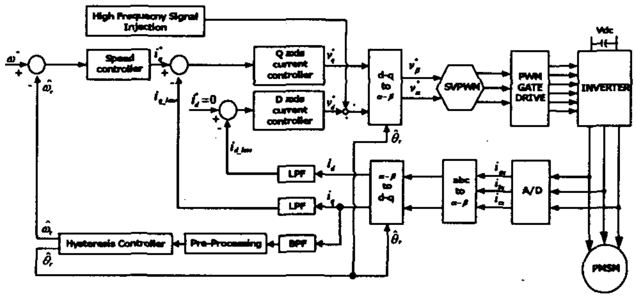
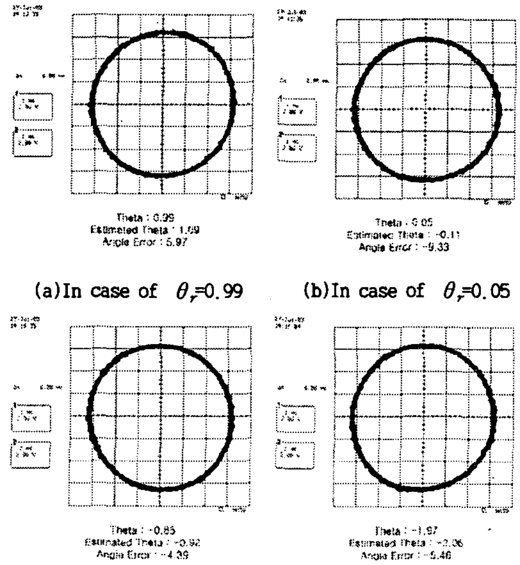


Fig. 5 Block diagram of the sensorless drive systetm

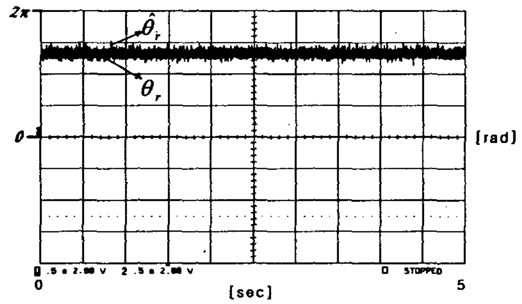


(a)In case of θ_r=0.99 (b)In case of θ_r=0.05

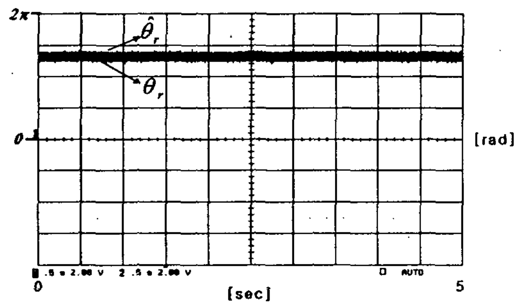
(c)In case of θ_r=-0.85 (d)In case of θ_r=-1.97

Fig. 6 Current ellipse in the stationary reference frame and the estimated initial rotor position

Fig. 6 shows the current ellipse in the stationary reference frame and the estimated initial rotor position. From the repeated test, rotor position is successfully detected within ±10° error in electrical degree.



(a)Conventional 2-Level Hysteresis Control



(b) Double Band 5-Level Hysteresis Control

Fig. 7 Estimated and actual rotor position when the 0rpm speed command

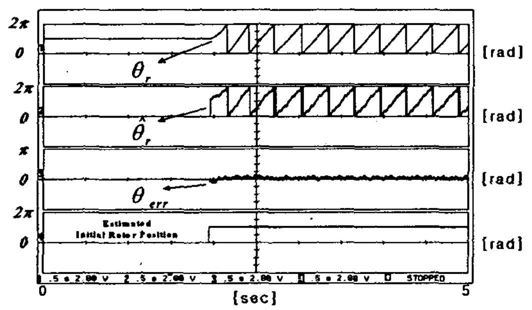


Fig. 8 Response of the proposed sensorless algorithm with 10rpm speed command

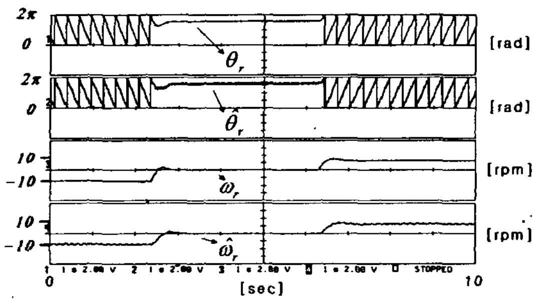


Fig. 9 Step response of the proposed algorithm (-10rpm → 0rpm → 10rpm)

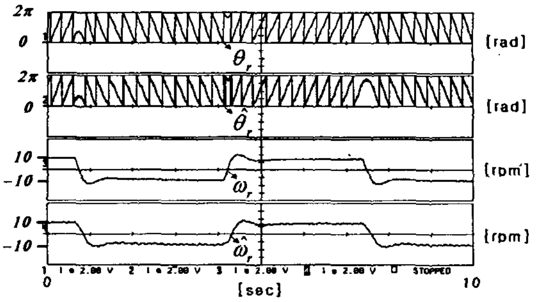


Fig. 10 Step response of the proposed sensorless algorithm (10rpm → -10rpm → 10rpm → -10rpm)

In Fig. 7, the double band hysteresis control shows a good reference tracking than the 2-level hysteresis control.

6. Conclusions

This paper presents the sensorless control of PMSM using high frequency voltage injection. Proposed sensorless control using double-band hysteresis controller and initial rotor position detection improves the stability, robustness and reference tracking. Also, it does not require the knowledge of any motor parameter, while it allows low cost implementation only requiring current sensors already included in standard drives. Experimental results verify the usefulness of the proposed algorithm.

References

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