sorless Model Predictive Current Control by Using HF Pulsating Injection Method for PMSM Drive System

Dongliang Lan¹, Haoyuan Li²,*, Shengbin Yu³

¹DaTang East China Electric Power Test & Research Institute, Hefei, China
²China Electric Power Research Institute, Nanjing, China
³China Qiyuan Engineering Corporation, Xinan, China

*Corresponding author e-mail: 1249288221@qq.com

Abstract. This paper presents the high frequency (HF) pulsating injection method based sensorless control combined with model predictive current control (MPCC) for permanent magnet synchronous motor (PMSM). The use of MPCC makes the implementation of sensorless algorithm difficult due to the lack of a modulator. Therefore, HF current signal is injected instead of normal voltage signal, which is more suitable for MPCC rather than filed orient control (FOC). Besides, three-vector-based MPCC is utilized, which can reduce the current ripple effectively and improve the steady-state performance. Finally, simulation results demonstrate the feasibility and effectiveness.

1. Introduction
Permanent magnet synchronous motor (PMSM) has the advantages of higher efficiency, higher performance, and compact construction, is widely used in electrical vehicle, traction, elevator fields [1]. Model predictive current control (MPCC) [2], takes into account the discrete states of the inverter instead of using a pulse width modulation concept. However, conventional PMCC faces the problems of large current ripple, unstable switching frequency and large amount of calculation. Therefore, three-vector-based MPCC [3] is utilized, which needs only six online predictive to obtain optimal voltage vector.

Usually, sensorless control algorithms are investigated and applied to get the position and speed information. Back electromotive force (EMF) based methods have shown good performance at high speed region, while magnetic saliency based methods show good candidate for low speed region. According to the type of injected high frequency (HF) signal, these methods contain HF rotating signal injection, HF pulsating signal injection, HF square-wave signal injection, etc. Among all of these methods, pulsating signal injection has the advantages of simple implementation and high accuracy [4].

However, many of the sensorless algorithms cannot be immediately used in conjunction with MPCC because its different way of operation with respect to a traditional linear controller and the absence of a modulator [5]. This paper investigates the feasibility of implementing a sensorless control for the PMSM low speed running in conjunction with MPCC. MPCC makes the HF voltage signal injection very difficult owing to the lack of a modulator. Therefore, HF current signal is injected and the position and speed information can be obtained by a type-II phase-locked loop (PLL). Simulation results prove out the effectiveness and practicability of the sensorless PMCC strategy.
2. Three-Vector-Based MPCC Strategy for PMSM Drive System

2.1 PMSM Discrete-Time Domain Model
When d-q axis current id and iq are chosen as state variables, the model of PMSM is described as

\[
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix}
= \begin{bmatrix}
    -\frac{R}{L_d} & \frac{\omega_L L_q}{L_d} \\
    -\frac{\omega_L L_d}{L_q} & -\frac{R}{L_q}
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix}
+ \begin{bmatrix}
    1 \\
    0
\end{bmatrix}
\begin{bmatrix}
    u_d \\
    u_q
\end{bmatrix}
+ \begin{bmatrix}
    0 \\
    -\frac{\omega_L \psi_f}{L_q}
\end{bmatrix}
\]

where R, Ld, Lq, \(\psi_f\) are stator resistance, d-axis inductance, q-axis inductance and permanent magnet flux linkage, respectively, p is differential operator. Switching to discrete-time domain using the Euler discretization method, the model is expressed as

\[
x(k+1) = \begin{bmatrix}
    1 & \frac{T}{L_d} & T L_q \omega_L \\
    -T L_q \omega_L & 1 & -\frac{T}{L_q} R
\end{bmatrix}
x(k) + \begin{bmatrix}
    0 \\
    0
\end{bmatrix} u(k) + \begin{bmatrix}
    0 \\
    -\frac{T \omega_L \psi_f}{L_q}
\end{bmatrix}
\]

(2)

2.2 Three-Vector-Based MPCC Strategy
Three-vector-based MPCC strategy uses two adjacent effective voltage vectors and one zero vector to synthesize an expected voltage vector equivalently in each sector. Six sectors synthesize six expected voltage vectors with variable directions and amplitudes as alternative voltage vectors. When zero vector is applied, the current slope of d-q axis can be presented as

\[
s_{d0} = \frac{di_d}{dt} \bigg|_{i_{d0}=0} = \frac{1}{L_q} \left[ -R i_d + \omega_L L_q i_q \right],
\quad
s_{q0} = \frac{di_q}{dt} \bigg|_{i_{q0}=0} = \frac{1}{L_q} \left[ -R i_q - \omega_L L_d i_d - \omega_L \psi_f \right]
\]

(3)

Similarly, when two adjacent effective voltage vectors are applied, the current slope of d-q axis can be presented as

\[
s_{d0} = \frac{di_d}{dt} \bigg|_{i_{d0}=0} + \frac{u_d}{L_d},
\quad
s_{q0} = \frac{di_q}{dt} \bigg|_{i_{q0}=0} + \frac{u_q}{L_q}
\]

\[
s_{d0} = \frac{di_d}{dt} \bigg|_{i_{d0}=0} + \frac{u_d}{L_d},
\quad
s_{q0} = \frac{di_q}{dt} \bigg|_{i_{q0}=0} + \frac{u_q}{L_q}
\]

(4)

Because the predicted value of the next sampling time is equal to the given value in deadbeat control, the predicted formulas of d-q axis current are as follows

\[
i_d(k+1) = i_d(k) + s_{d0} i_d + s_{q0} i_q + s_{d0} \psi_f = i_d^*,
\quad
i_q(k+1) = i_q(k) + s_{d0} i_d + s_{q0} i_q + s_{d0} \psi_f = i_q^*
\]

(5)

Besides, the expression of the expected voltage vector is

\[
u_d = \frac{i_d}{T_i} u_{d0} + \frac{i_q}{T_i} u_{q0},
\quad
u_q = \frac{i_d}{T_i} u_{d0} + \frac{i_q}{T_i} u_{q0}
\]

(6)
3. Sensorless MPCC Using HF Pulsating Current Injection Method

3.1 HF Pulsating Current Signal Injection

With assumptions that the PMSM is unsaturated, eddy currents and hysteresis losses are negligible. When the injected current frequency is sufficiently high, the back electromotive force and resistance voltage drop can be neglected, then the d-q axis voltage function can be rewritten as

\[
\begin{bmatrix}
u_d \\ u_q \\
\end{bmatrix} = \begin{bmatrix} pL_d & 0 \\ 0 & pL_q \\
\end{bmatrix} \begin{bmatrix} i_d \\ i_q \\
\end{bmatrix}
\]  

(7)

If the angle error between actual and estimated d-q axis is \( \Delta \theta_r \), the estimated d-q axis voltage function can be derived as

\[
\begin{bmatrix}
\hat{u}_d \\ \hat{u}_q 
\end{bmatrix} = \begin{bmatrix} L_0 + L_1 \cos 2\Delta \theta_r & L_1 \sin 2\Delta \theta_r \\ L_1 \sin 2\Delta \theta_r & L_0 - L_1 \cos 2\Delta \theta_r 
\end{bmatrix} \begin{bmatrix} p\hat{i}_d \\ p\hat{i}_q 
\end{bmatrix}
\]  

(8)

where \( L_0 \) is average inductance, \( L_1 \) is differential inductance, \( L_0 = (L_d + L_q)/2 \), \( L_1 = (L_d - L_q)/2 \). A high frequency (HF) current is injected into estimated d-q axis, which is expressed as

\[
\begin{bmatrix}
\hat{i}_{dh} \\ \hat{i}_{qh} 
\end{bmatrix} = \begin{bmatrix} V_s \cos \omega_f t \\ 0 
\end{bmatrix}
\]  

(9)

Then estimated d-q axis HF voltage is derived as

\[
\begin{bmatrix}
\hat{u}_{dh} \\ \hat{u}_{qh} 
\end{bmatrix} = \begin{bmatrix} l_p + l_s \cos 2\Delta \theta_r \\ l_s \sin 2\Delta \theta_r 
\end{bmatrix} \sin \omega_f t
\]  

(10)

A type-II phase-locked loop (PLL) structure is used to make \( \hat{u}_{qh} \) converge to zero. Alternatively, \( \sin \omega_f t \) is used as the multiplier, combing with a low-pass filter (LPF) to extract the position deviation signal \( f(\Delta \theta_r) \), which is expressed as

\[
f(\Delta \theta_r) = \text{LPF} [\hat{u}_{qh} \sin \omega_f t] = V_s l_s \sin 2\Delta \theta_r f/2
\]  

(11)

3.2 Sensorless MPCC Strategy

The complete block diagram of the sensorless MPCC strategy is depicted in Figure 1. The strategy consists of HF pulsating current injection based estimator which provides estimated position and speed to MPCC. MPCC generates voltage vector and the applies to the PMSM via voltage source inverter (VSI).

\[\text{Figure 1. Block diagram of the sensorless MPCC strategy.}\]
4. Simulation Results
The MPCC with the HF pulsating current injection based estimator has been simulated on a 18kW PMSM. The PMSM drive system parameters are listed in Table 1. The comparison of steady-state performance of d-q axis current adding HF pulsating current is shown in Figure 2. Field oriented control (FOC) is applied as shown in Figure 2(a), in order to compare with MPCC as shown in Figure 2(b). It is noted that MPCC has better current tracking ability than FOC, and the ripple is much smaller under the low switching frequency condition.

Table 1. Parameters of PMSM Drive System

| Symbol | Quantity | Value   | Symbol | Quantity | Value   |
|--------|----------|---------|--------|----------|---------|
| $P$    | Rated power | 18 kW   | $f_s$  | Switching frequency | 4000 Hz |
| $n_p$ | Pole pairs | 4       | $U_{dc}$ | DC link voltage | 380 V   |
| $R$    | Resistance | 0.06 Ω  | $t_d$  | Dead time | 2.5 μs  |
| $L_q$  | $q$-axis inductance | 1.04 mH | $\psi_f$ | Flux linkage | 0.1005 Wb |
| $L_d$  | $d$-axis inductance | 0.31 mH | $n$    | Rated speed | 3000 rpm |

![Figure 2](image.png)

**Figure 2.** Comparison of steady-state performance of d-q axis current adding HF pulsating current. (a) Simulation results of sensorless FOC strategy. (b) Simulation results of sensorless MPCC strategy.

The dynamic performance of sensorless MPCC strategy is shown in Figure 3. In Figure 3(a), rotor speed reverses from -60rpm to 60rpm at 25% rated load. It is noted that the estimated position can always track the actual position. Furthermore, load step test is shown in Figure 3(b), the position estimator can operate stably from no load to 25% load at 30rpm.
**Figure 3.** Simulation results of dynamic performance of sensorless MPCC strategy. (a) Rotor speed reverses from -60rpm to 60rpm at 25% rated load. (b) Load step test (from no load to 25% load) at 30rpm.

Furthermore, parameter robustness simulation is carried out and shown in Figure 4. The increase by 10% and decrease by 50% in q axis inductance is shown in Figure 4(a), and the increase by 5% and decrease by 50% in d axis inductance is shown in Figure 4(b), the estimator works stably. However, when the inductance increase more the system will be unstable, which means the inductance used in MPCC should be the value at no load. The variations in resistance and flux linkage by ±50% do not have any significant effects on estimated position as shown in Fig. 4(c) and (d) respectively.

**Figure 4.** Parameters robustness simulation results with sensorless MPCC strategy. (a) +10% and -50% variation in Lq. (b) +5% and -50% variation in Ld. (c) ±50% variation in R. (d) ±50% variation in ψf.
5. Conclusion
The paper presents the HF pulsating current injection based position estimation for PMSM drive with MPCC. It is shown the proposed method is an ideal solution for HF current injection with MPCC, due to MPCC has better current tracking ability than FOC. The feasibility of sensorless MPCC strategy is analyzed in this paper and the overall control block diagram is presented. The simulation results proves out the effectiveness and practicability of sensorless MPCC strategy. The future work will be focused on improving the system stability and load capacity. More details will be shown in the final paper.

References
[1] H. Zhan, Z. Q. Zhu and M. Odavic, “Nonparametric sensorless drive method for open-winding PMSM based on zero-sequence back EMF with circulating current suppression,” IEEE Transactions on Power Electronics, vol. 32, no. 5, pp. 3808-3817, May 2017.
[2] Yanping Xu, Baocheng Zhang and Qin Zhou, "A model predictive current control method of PMSM based on the simultaneous optimization of voltage vector and duty cycle," 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), Hefei, 2016, pp. 881-884.
[3] Yanping Xu, Jibing Wang, Baocheng Zhang, et al., “Three-vector-based model predictive current control for permanent magnet synchronous motor”, Transactions of China Electrotechnical Society, vol. 33, no. 5, pp. 980-988, May 2017.
[4] X. Luo, Q. Tang, A. Shen, et al., "PMSM sensorless control by injecting HF pulsating carrier signal into estimated fixed-frequency rotating reference frame," IEEE Transactions on Industrial Electronics, vol. 63, no. 4, pp. 2294-2303, April 2016.
[5] L. Rovere, A. Formentini, A. Gaeta, et al., "Sensorless finite-control set model predictive control for IPMSM drives," IEEE Transactions on Industrial Electronics, vol. 63, no. 9, pp. 5921-5931, Sept. 2016.