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An adaptive sliding-mode observer with a tangent function-based PLL structure for position sensorless PMSM drives

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A B S T R A C T

This paper proposes a position estimation strategy for the sensorless control of permanent-magnet synchronous motors (PMSMs) based on an improved sliding-mode observer (SMO) and a tangent function-based phase-locked loop (PLL) structure. The improved SMO adopts a rotor speed-related adaptive feedback gain, and is able to derive a flux model-based estimator that contains rotor position and speed direction information. To extract accurate rotor position from the proposed SMO and reduce position estimation errors in both forward and reverse rotation of the PMSM, a tangent function-based PLL structure is established. The proposed SMO together with the PLL structure realises a solution to position and speed estimation for sensorless PMSM drives. Compared with the conventional back electromotive force (EMF)-based position estimator, the proposed position estimation strategy has advantages of simple design and robust estimation performance at a wider speed range. Effectiveness of the proposed method has been validated with simulations on virtual platform.

1. Introduction

Permanent magnet synchronous motors (PMSMs) have been widely used as servo motors in high-dynamic and high-precision applications, because of their high power density and efficiency. Field orientation control strategies of these motors require precise knowledge of real-time rotor position and speed, which are normally measured by mechanical position sensors mounted on rotor shafts, such as shaft encoders, resolvers and Hall sensors [1]. However, installing additional sensors will increase size, cost, and mechanical failure probability of the drives, thus limits usage of the PMSM under certain environmental conditions.

To resolve these problems, sensorless control methods using estimated position and speed of the rotor have been developed [2–5]. Since the PMSM back electromotive force (EMF) contains information about rotor position and speed, estimation methods based on the back-EMF are widely utilised [6,7]. These methods mainly include the Kalman filtering method, the model adaptive method, the Luenberger state observer, the disturbance observer, and the sliding mode observer (SMO), etc. [8–13]. Among these methods, SMO possesses benefits of simple structures, resistance to disturbances, and low sensitivity to parameter perturbations, so it is often applied to sensorless PMSM drives [14].

In earlier SMO methods, a signum function is utilised as the sliding-mode switching function. Due to the discontinuous feature of the signum function, a low-pass filter (LPF) is required to smooth the estimated back-EMF signals and position compensation should be considered because the LPF brings in system phase delay. To reduce the SMO chattering phenomenon and avoid usage of the LPF, a continuous sigmoid function is introduced to replace the signum function [15–17]. Although this method performs well in reducing chattering, two challenges for such SMO remain to be dealt with. First, magnitude of the back-EMF varies greatly with different rotor speeds; at relatively low speed, the induced back-EMF values are very small to be accurately estimated [18]. Second, within the full operating speed range, the switching gain for either signum or sigmoid function-based SMO needs to be sufficiently large to satisfy the Lyapunov stability condition for convergence of estimation errors. High switching gain will in turn cause large chattering of the estimated signals, especially in low speed range [19].

To extract position and speed information within the observed back-EMF values, a phase-locked loop (PLL) is utilised in many research works [20–22]. The PLL structure applied in these works, which is described as the conventional PLL in this paper, is the one with an estimation error proportional to sinusoidal function [23]. It

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should be noted that this conventional PLL loses its accuracy when speed reversal happens to the PMSM. In fact the structure of this PLL inherently requires a normalisation procedure in practice and the PLL parameters should be re-designed once the PMSM changes speed direction. Such drawback appearing during speed reversal is essentially stem from the fact that sign of the back-EMF shape function has influence on the sign of the PLL estimation error function. This feature due to the PLL structure subsequently limits its applications. To conquer this problem, [24,25] have proposed a PLL scheme with its estimation error proportional to a tangent function. This particular PLL scheme has later been exploited in applications such as BLDC control of micro aerial vehicles [26].

On the basis of sigmoid switching function, this paper proposes an improved SMO with a rotor speed-related adaptive feedback gain. A flux model-based position estimator is derived from the proposed SMO, and it is independent of rotor speed. The flux model-based estimator, instead of the observed back-EMF, is used for position information extraction. As a result of independency of rotor speed, the position estimator manage to provide a robust estimation performance within relatively low speed range. To overcome aforementioned limitations of the conventional PLL, a tangent function-based PLL structure, which has the similar design principle to the PLL in [24,25], is proposed to meet applications in which both positive and negative speed of the PMSM is required. Generalised form of such tangent function-based PLL and its estimation error dynamics are summarised and analysed in detail. The improved SMO together with the proposed PLL structure forms the PMSM rotor position and speed estimation solution. Effectiveness of the proposed method is verified with simulations on a 1.1 kW industrial position sensorless PMSM drive.

The rest of the paper is organised as follows. Section 2 first introduces the conventional sigmoid function-based SMO, followed by a detailed inspection of its properties, and then the improved SMO method is presented. Section 3 analyses limitations of the conventional PLL, and establishes the tangent function-based PLL structure. Section 4 illustrates simulation results of the proposed estimation solution. Finally, a conclusion closes the paper.

2. SMO design for the PMSM

2.1. Dynamic model of a non-salient PMSM

Assuming that the PMSM has symmetrical windings, system dynamics of a PMSM under rotational $d-q$ reference frame can be expressed as

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} R_s + L_q \frac{d}{dt} & w_r L_d \\ -w_r L_q & R_s + L_d \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} w_r \lambda_{af} \\ 0 \end{bmatrix} \tag{1}$$

where $\frac{d}{dt}$ is the derivative operator; v_d, v_q are the d-axis and q-axis stator voltages, respectively; i_d, i_q are the d-axis and q-axis stator currents, respectively; L_q and L_d are the inductances of d, q axes, satisfying $L_d = L_q = L_s$ for non-salient PMSMs; R_s is the stator-winding resistance; w_r is the rotor electrical speed, and λ_{af} is the flux linkage produced by permanent magnets.

Using the inverse Park transformation, the non-salient PMSM model in the stationary $\alpha-\beta$ reference frame is presented as

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = R_s \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \tag{2}$$

where v_α, v_β are the α-axis and β-axis stator voltages, respectively; i_α, i_β are the α-axis and β-axis stator currents, respectively, and θ_r is the rotor electrical position. e_α and e_β represent the back-EMF of α-axis and β-axis, satisfying $e_\alpha = -w_r \lambda_{af} \sin\theta_r$ and $e_\beta = w_r \lambda_{af} \cos\theta_r$.

It can be observed that back-EMF signals contain information of both the PMSM rotor electrical position and speed.

2.2. Conventional SMO

By using mathematical model of PMSM in the $\alpha-\beta$ reference frame, the typical SMO method can be expressed as

$$\begin{cases} L_s \frac{d\hat{i}_\alpha}{dt} = v_\alpha - R_s \hat{i}_\alpha - k \cdot \operatorname{sgn}(\hat{i}_\alpha - i_\alpha) \\ L_s \frac{d\hat{i}_\beta}{dt} = v_\beta - R_s \hat{i}_\beta - k \cdot \operatorname{sgn}(\hat{i}_\beta - i_\beta) \end{cases} \tag{3}$$

where " ^ " denotes the estimation value, k is a positive constant observer gain, and sgn() represents the signum function. Subtracting Eq. (2) from (3), and current estimation error $\tilde{i}(\tilde{i} = \hat{i} - i)$, can be derived as

$$\begin{cases} L_s \frac{d\tilde{i}_\alpha}{dt} = -R_s \tilde{i}_\alpha - (k \cdot \operatorname{sgn}(\tilde{i}_\alpha) - e_\alpha) \\ L_s \frac{d\tilde{i}_\beta}{dt} = -R_s \tilde{i}_\beta - (k \cdot \operatorname{sgn}(\tilde{i}_\beta) - e_\beta) \end{cases}. \tag{4}$$

The sliding surface corresponding to the zero-error manifold is defined as

$$S = [s_\alpha \quad s_\beta]^T = \left[\tilde{i}_\alpha \quad \tilde{i}_\beta\right]^T. \tag{5}$$

If the SMO gain k is large enough, $k > \max(|e_\alpha|, |e_\beta|)$, leading $S^T \cdot \dot{S} < 0$, the estimation errors can converge to $S = 0$, namely the observed values in Eq. (3) can be used to approximate back-EMF of the rotor:

$$k \begin{bmatrix} \operatorname{sgn}(s_\alpha) \\ \operatorname{sgn}(s_\beta) \end{bmatrix} = \begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} = w_r \lambda_{af} \begin{bmatrix} -\sin\theta_r \\ \cos\theta_r \end{bmatrix}. \tag{6}$$

However, the discontinuous property of the signum function causes large ripples in back-EMF estimation results. To reduce chattering phenomenon of the SMO and exempt LPF from the system, a continuous sigmoid function is used to replace sgn(). The sigmoid function is defined as

$$F(s) = \left[\frac{2}{(1 + e^{-as})} - 1\right] \tag{7}$$

where a is a positive adjustable parameter. The same sliding manifold S in (5) is selected and the conventional sigmoid-function based SMO can be rewritten as

$$\begin{cases} L_s \frac{d\hat{i}_\alpha}{dt} = U_\alpha - R_s \hat{i}_\alpha - kF(s_\alpha) \\ L_s \frac{d\hat{i}_\beta}{dt} = U_\beta - R_s \hat{i}_\beta - kF(s_\beta) \end{cases}. \tag{8}$$

2.3. Design of the improved sigmoid function-based SMO

To verify stability of the SMO in Eq. (8), a Lyapunov function based on the sliding surface S is selected as

$$V = \frac{1}{2} S^T S. \tag{9}$$

Differentiating V with respect to time gives

$$\begin{aligned} \dot{V} &= S^T \dot{S} \\ &= -\frac{R_s}{L_s}\left[s_\alpha^2 + s_\beta^2\right] \\ &\quad + \frac{1}{L_s}\left[e_\alpha - kF(s_\alpha)\right] \cdot s_\alpha \\ &\quad + \frac{1}{L_s}\left[e_\beta - kF(s_\beta)\right] \cdot s_\beta. \end{aligned} \tag{10}$$