Sensorless Control of a Tubular Oscillatory LPMSM based on MARS and Deadbeat Current Predictive Control

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Abstract. In the vector control system of the tubular oscillatory linear permanent magnet (PM) synchronous motor (LPMSM), it is difficult for traditional mechanical sensors to accurately obtain the feedback information under harsh conditions. In this work, a speed sensorless vector control system is designed and applied to the tubular oscillatory LPMSM which adopts the model reference adaptive system (MRAS), and the deadbeat current predictive control (DCPC) is also adopted to replace the traditional PI current loop to establish the coordination controller, which overcomes the difficulties of global optimization and PI control parameter setting. And the method is proved by the simulation results and it gets better dynamic performance.

1. Introduction

The tubular oscillatory LPMSM has compact structure, and it is more efficient. And they have been widely used in industry and other fields in the last decades [1]-[4]. In order to get high performance, it is required for the LPMSM which using vector control to get the rotational position and speed. The position sensors such as encoders are often used to measure them [5].

In addition, LPMSMs can use back electromagnetic force (EMF) or saliency effects to estimate simpler sensorless rotor positions, which avoids the installing position sensors. In this way, it can eliminate the fragile parts from the system and significantly reduce the overall driving cost and size.

The most commonly used sensorless control algorithms can be divided into two categories. The one is to use the basic excitation technique to get the estimated rotational speed and position using back EMF which produced by the PM. And the other approach is based on the saliency tracking technique, and it injects the persistent high-frequency signals by using the rotor anisotropy, thus getting the position information [6]-[8].

The MRAS is commonly used for the evaluation of rotational position and speed, and it is easily to implement in vector control. In references [9]-[12], the MAR9 method based on the stator flux vector is adopted for the calculation of stator flux by voltage and current model, respectively. The adaptive algorithm is used to tinker up the stator flux calculated by the above two models, which achieving the purpose of observing the speed of the motor.

The deadbeat current predictive control (DCPC) algorithm predicts the switching signal of the inverter at the next moment on the basis of the mathematical model [13]. This algorithm provides the control system with low torque ripple and high current frequency response, which can obtain higher dynamic response performance.
The feasibility of realizing the sensorless control of tubular oscillation LPMSM is discussed. And the MARS and DCPC is adopted.

2. Control Algorithm

To realize the sensorless control of tubular oscillatory LPMSM, the MARS is adopted. And the DCPC is presented to replace the traditional PI current loop.

2.1. Sensorless control using MARS

The basic structure of MARS is shown as the following Fig. 1. The reference model choses the mathematical model of LPMSM, besides, the adjustable model choses the state matrix which containing primary speed information.

\[
\begin{align*}
    u_d &= R_s i_d + L_d \frac{di_d}{dt} - \frac{\pi}{\tau} v L_q i_q \\
    u_q &= R_s i_q + L_q \frac{di_q}{dt} + \frac{\pi}{\tau} v (L_d i_d + \psi_f) 
\end{align*}
\]

\[\text{(1)}\]

where \(u_d, u_q\) are the axis stator voltages, \(i_d, i_q\) are the stator currents, and \(\psi_d, \psi_q\) are the axis flux linkages, \(\psi_f\) rotor permanent magnet flux. \(R_s\) is the stator resistance and \(L_q, L_d\) are the axis inductance. \(\tau\) is the pole pitch and \(v\) is the synchronous speed.

The Eq. (2) shows the electromagnetic torque equation of the LPMSM:

\[
T_e = \frac{3}{2} p \left[ \psi_f i_q + i_d i_q (L_d - L_q) \right]
\]

\[\text{(2)}\]

The reference model is as Eq. (1), and it shows the mathematical model of the LPMSM in the \(d\ q\) frame of axes.

\[
\begin{align*}
    \frac{di_d}{dt} &= \frac{u_d}{L_d} - \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \frac{\pi}{\tau} v \\
    \frac{di_q}{dt} &= \frac{u_q}{L_q} - \frac{R_s}{L_q} i_q - \frac{L_d}{L_q} \frac{\pi}{\tau} v - \frac{\psi_f}{\tau} \frac{\pi}{\tau} v 
\end{align*}
\]

\[\text{(3)}\]

The adjustable model which contain the speed is as Eq. (4). The MARS can be used to estimate the velocity by estimating the \(d, q\)-axis current.

\[
\dot{v} = \left( K_p + K_i \frac{s}{s} \right) \left[ i_q \dot{i}_q - \dot{i}_d i_d - \frac{\psi_f}{L_q} (i_q - \dot{i}_q) \right] + \dot{v}(0)
\]

\[\text{(4)}\]
where \( \hat{\nu} \) is the estimated speed, \( \hat{i}_d, \hat{i}_q \) d-, q- stator axis estimated current.

The angle is obtained by an integral over Eq. (4)

\[
\dot{\theta}_e = \int \frac{\pi}{\tau} \hat{\nu} dt
\]

(5)

2.2. Deadbeat current predictive control

The sampling time \( T_s \) is extremely small and it can be neglected. Therefore, the Eq. (3) can be discretized using the first-order Taylor formula. It can be approximated to have the Eq. (6):

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{i_d(t+1) - i_d(t)}{T_s} \\
\frac{di_q}{dt} &= \frac{i_q(t+1) - i_q(t)}{T_s}
\end{align*}
\]

(6)

For the tubular oscillatory LPMSM, \( L_d = L_q = L \). Applying the Eq. (6) ahead to (5), and rearranging the equations, the discretized current prediction model of LPMSM is obtained:

\[
\begin{align*}
i_d(t+1) &= \frac{T_s}{L} \left[ u_d(t) - R_d i_d(t) + L \frac{\pi}{\tau} \nu(t) i_q(t) \right] + i_d(t) \\
i_q(t+1) &= \frac{T_s}{L} \left[ u_q(t) - R_q i_q(t) - L \frac{\pi}{\tau} \nu(t) i_d(t) - L \frac{\pi}{\tau} \psi f \nu(t) \right] + i_q(t)
\end{align*}
\]

(7)

Using the reference current \( i_d^*(t) \), \( i_q^*(t) \) as the input current \( i_d(t+1), i_q(t+1) \) of instant \((t+1)\), and the current \( i_d(t) \) and \( i_q(t) \) can be obtained by the three-phase current through mathematical frame axes transformation. The Eq. (3) shows the mathematical model of voltage:

\[
\begin{align*}
u_d(k) &= L \left( \frac{i_d^*(t) - i_d(t)}{T_s} \right) + R_d i_d(t) - L \frac{\pi}{\tau} \nu(t) i_q(t) \\
u_q(k) &= L \left( \frac{i_q^*(t) - i_q(t)}{T_s} \right) + R_q i_q(t) + L \frac{\pi}{\tau} \nu(t) i_d(t) + \frac{\pi}{\tau} \psi f \nu(t)
\end{align*}
\]

(8)

3. Simulation Analysis

The method is simulated and analyzed. The Fig. 2 shows the control structure of the method. The speed loop uses a standard proportional integral controller. And the DCPC has been used for the current loop. The MARS block implements the computation of the rotor position and speed.

In the vector control of LPMSM, the \( i_d^* \) is controlled to zero, the reference speed \( \nu^* = 1 \text{ m/s} \), and the information of the parameters that adopted in the simulation model are shown in Table I. Fig.3-5 show the simulation results.
Deadbeat current predictive control

Figure 2. Complete control structure.

Table 1. Simulation Parameters

| Name | Value | Unit |
|------|-------|------|
| $L$  | 0.0085 | [H]  |
| $R_s$ | 2.875  | [Ω]  |
| $\psi_f$ | 0.175  | [Wb] |
| $p$  | 4     | -    |
| $\tau$ | 0.0032 | [m]  |

Fig. 3 shows the simulation results of no-load starting performance. It can be noticed from the figures that the LPMSM has a good output response performance, the simulation model can follow the given speed very well. At steady state, the electromagnetic thrust response is almost maintained near 0. Fig. 4–5 show the simulation results load mutation at 0.5s. The speed falls partly but soon follows the given speed and reaches a stable running state, and the electromagnetic torque follows load torque well.

Figure 3. Simulation results of no-load starting performance. First: estimated speed. Second: estimated position. Third: three-phase currents. Last: electromagnetic thrust.
Figure 4. Simulation result of estimated speed with load mutation at 0.5s.

Figure 5. Simulation results with load mutation at 0.5s. First: estimated position. Second: three-phase currents. Third: electromagnetic thrust.

4. Conclusion
This paper has introduced the sensorless control of tubular oscillatory LPMSM based on MARS and DCPC. The simulation results show that the LPMSM has a good output response performance, and the estimation speed and rotor position satisfy the control performance requirements.

Furthermore, the proposed method will be tested on an experimental setup in the future.
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