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Sensor-less Complex System Control of PMSM Based on Improved SMO

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Abstract—**The sensor-less control system of PMSM is complicated, and it is of great significance to carry out accurate mathematical modeling and simulation analysis. PMSM is small in size, high in efficiency, and low in noise, so it is very popular in AC motor applications. They have been widely used in various electrical appliances such as machine tools, robots, and household appliances. In order to reduce the high-frequency chatter of the sensor-less control strategy of permanent magnet synchronous motors, a sensor-less control method based on improved SMO is proposed. The back-EMF component in the static coordinate system is obtained through the SMO. The back-EMF component undergoes closed-loop feedback to eliminate the high-frequency components. The back-EMF component is calculated by an improved PLL to obtain the position and speed of the rotor to improve system performance. At the end of the article, the feasibility is proved by comparing it with the simulation of conventional SMO-PLL.**

Keywords—PMSM, SMO with closed-loop feed back, improved PLL

I. INTRODUCTION

With the gradual expansion of the application of simulation technology in various fields of research and engineering practice, there are more and more simulation systems and models in various fields. The construction of fidelity and high-precision system models involves the integration of different levels of models such as systems, subsystems, and components. Ensuring the high efficiency, low cost, and high reliability of simulation applications is the urgent need and focus of current complex system simulation.Using position and speed sensors is a quick and effective method to directly measure information of PMSM of the rotor speed and position. However, this method still has disadvantages such as large volume, high cost, many leads, and increased environmental requirements. To overcome the impact of mechanical position sensors on the control system's cost and reliability, many scholars have studied the sensor-less control methods of PMSM in recent decades [1] , and various permanent magnet synchronous motor sensor-less control methods have been successively popped up. At present, the sensor-less control methods of surface-mounted PMSM mainly include the high-frequency signal injection method and back-EMF method, which are respectively suitable for low-speed and medium-high-speed areas. Sensor-less control technology generally means that in the speed control system, no mechanical sensor is installed to directly measure the position and speed of the motor's rotor, to use the measurable electrical signal of the engine to estimate the rotor's speed and position information through an algorithm. The SMO stands out due to its advantages, such as being less affected by motor parameter changes, robust external interference, and short response time [2]. Literature [3] proposed an adaptive back-EMF error observer to track the rotor's speed and position, thereby avoiding complicated calculations and reducing system jitter. In the literature [4], the estimated value of back-EMF in the static coordinate system is obtained by extending the SMO. The speed observer is established by the model reference adaptive method to get the estimated value of speed and the new back EMF. The back-EMF is brought into the position angle is obtained by processing in the improved phase-locked loop. In the literature [5], the author establishes a nonlinear equivalent SMO model to optimize the position estimation error. The position error under variable speed is solved by adding feed-forward to the PLL. In the literature [6], the extended back-EMF estimated value is fed back to the stator current observation link to obtain an extended SMO, which effectively improves the chattering problem existing in the extended SMO. Literature [7] proposed an adaptive fuzzy sliding mode observer to realize PMSM sensor-less control. Literature [8] uses an extended Kalman filter. The device observes and filters the motor's back-EMF and achieves the suppression of chattering—the effect of vibration. Literature [9] in the view of the sliding model low-pass filter with a variable cut-off frequency is designed in the detector, which effectively suppresses the chattering phenomenon of the system.

Aiming at the problem of reduced accuracy of rotor position and speed estimation during the operation of position

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sensor-less, a position sensor-less control method based on closed-loop feedback of back-EMF by an SMO is proposed. the back-EMF of the static coordinate system is obtained through the SMO. The chattering component in the back-EMF is eliminated through the subsequent closed-loop feedback module to improve the dynamic performance of the system. The mathematical model of PMSM is established based on the id=0 vector control principle. Secondly, the conventional SMO is improved by combining the back-EMF closed-loop feedback and the improved phase-locked loop technology.

II. DESIGN OF CONVENTIONAL SMO

PMSM'S mathematical model in the two-phase static coordinate system:

$$\frac{d}{dt}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = -\frac{R_S}{L_S}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{1}{L_S}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{1}{L_S}\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \tag{1}$$

among them: $\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \omega_e \psi_f \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix}$

where R_s is the stator resistance; L_s is the stator inductance; ω_e is the actual electrical angular velocity; $\begin{bmatrix} u_\alpha & u_\beta \end{bmatrix}^T$ is the stator voltage in the static coordinate system; $\begin{bmatrix} i_\alpha & i_\beta \end{bmatrix}^T$ is the stator current in the fixed coordinate system; $\begin{bmatrix} e_\alpha & e_\beta \end{bmatrix}^T$ is the back electromotive force in the stationary coordinate system; θ_e is the rotor position. ψ_f is the rotor flux. In (1) , the rotor's position information exists in the back-EMF, so with an accurate value of the back-EMF, the motor's speed and position can be calculated.

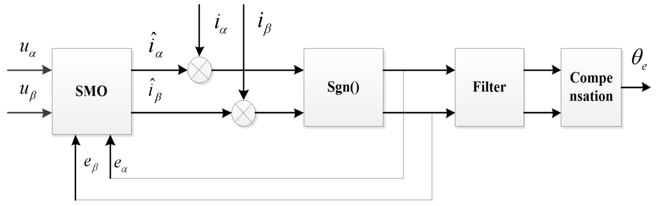


Fig. 1. Flow chart of conventional sliding model observer

The switching function adopted by the conventional SMO will introduce high-frequency chattering. Generally, using a low-pass filter eliminates chattering, but then there will be a phase lag problem. To reduce the influence of filter lag on the back- EMF, the back EMF observation value is fed back to the stator current sliding mode observation value. Construct the SMO here as follows:

$$\frac{d}{dt}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} = -\frac{R_S}{L_S}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} + \frac{1}{L_S}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{1}{L_S}\begin{bmatrix} e_\alpha - v_\alpha \\ e_\beta - v_\beta \end{bmatrix} \tag{2}$$

Where $\hat{i}_\alpha$ 、 $\hat{i}_\beta$ is the observed value of the stator current sliding mode; $\hat{e}_\alpha$ 、 $\hat{e}_\beta$ is the practical value of the stator back-EMF; v_α 、 v_β is the error switching function.

Define the sliding surface s:

$$s = \begin{bmatrix} s_\alpha & s_\beta \end{bmatrix}^T = \begin{bmatrix} \tilde{i}_\alpha & \tilde{i}_\beta \end{bmatrix}^T \tag{3}$$

Where $\tilde{i}_\alpha = \hat{i}_\alpha - i_\alpha$ 、 $\tilde{i}_\beta = \hat{i}_\beta - i_\beta$ is the current observation error, take the derivative of the sliding mode surface and bring it into the (1):

$$\frac{d}{dt}\begin{bmatrix} s_\alpha \\ s_\beta \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} + \frac{R_S}{L_S}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{1}{L_S}\begin{bmatrix} e_\alpha - u_\alpha \\ e_\beta - u_\beta \end{bmatrix} \tag{4}$$

When the SMO moves on the sliding mode trajectory, $s = \begin{bmatrix} s_\alpha & s_\beta \end{bmatrix}^T = 0$ the observed value of the stator back-EMF at this time is:

$$\begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} = -L_S\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} - R_S\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \begin{bmatrix} k_m sat(s_\alpha) \\ k_m sat(s_\beta) \end{bmatrix} \tag{5}$$

Where k_m is the SMO's gain, keeping the sliding mode gain always greater than zero; sat () is a continuous function. The equation (5) is designed as the sliding mode control law of the SMO, and the Lyapunov function is used to verify:

Suppose the function is $V_1 = 0.5(s_\alpha^2 + s_\beta^2)$ differentiated V_1 and substituted into (4) to get:

$$\begin{aligned} \dot{V}_1 &= s_\alpha \dot{s}_\alpha + s_\beta \dot{s}_\beta \\ &= -k_m s_\alpha sat(s_\alpha) - k_m s_\beta sat(s_\beta) \\ &= -k_m |s_\alpha| - k_m |s_\beta| < 0 \end{aligned} \tag{6}$$

This proves the stability of the control system. Substituting (2) into (5) to obtain the error switching function:

$$\begin{bmatrix} v_\alpha & v_\beta \end{bmatrix}^T = \begin{bmatrix} k_m sat(\hat{i}_\alpha - i_\alpha), & k_m sat(\hat{i}_\beta - i_\beta) \end{bmatrix}^T \tag{7}$$

Combining (7) and (2) can obtain the stator back electromotive force's predicted value. Fig. 1 is the control flow of the conventional SMO.

III. SMO BASED ON CLOSED LOOP FEEDBACK

A. Closed-loop feedback module design

It can be known from the mathematical model of the motor:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \omega_e \varphi_f \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} \tag{8}$$

Derivation of both ends of (9) can be obtained:

$$\begin{aligned} \frac{d}{dt}e_\alpha &= \frac{d}{dt}(-\omega_e \varphi_f \sin\theta_e) \\ &= -\varphi_f \sin\theta_e \frac{d}{dt}\omega_e - (\omega_e \varphi_f \cos\theta_e)\omega_e \end{aligned} \tag{9}$$

During the rotor operation, the current sampling frequency is very high, and the rate of change of speed is much lower than the rate of change of current. Therefore, the derivation of (9) can be simplified to (10):

$$\begin{cases} \dfrac{d}{dt}e_\alpha \approx -\omega_e e_\beta \\ \dfrac{d}{dt}e_\beta \approx \omega_e e_\alpha \end{cases} \tag{10}$$

From (10), we can extend (11):

$$\begin{cases}\frac{d}{dt}e_\alpha \approx -\omega_e e_\beta - n\tilde{e}_\alpha \\ \frac{d}{dt}e_\beta \approx \omega_e e_\alpha - n\tilde{e}_\beta\end{cases} \tag{11}$$

In the equation, $\tilde{e}_\alpha = \hat{e}_\alpha - e_\alpha$, $\tilde{e}_\beta = \hat{e}_\beta - e_\beta$ is the back-EMF observation error, n is the back-EMF observation error coefficient. The value range of n is greater than zero.

Based on (11), we can construct a back-EMF closed-loop feed-back model at the SMO's output, as shown in Fig 1. Use a closed-loop feed-back model to replace the transmission. The closed-loop feed-back model is used to replace the conventional low-pass filter to solve the phase lag problem caused by the low-pass filter to improve the back-EMF estimation accuracy.

B. Improved PLL Design

The conventional PLL has certain drawbacks, In literature [10], a phase-locked loop with a link that eliminates the influence of rotation is designed to eliminate the influence of speed changes. So the pre-feedback and post-compensation are introduced into the phase-locked loop(Fig. 2):

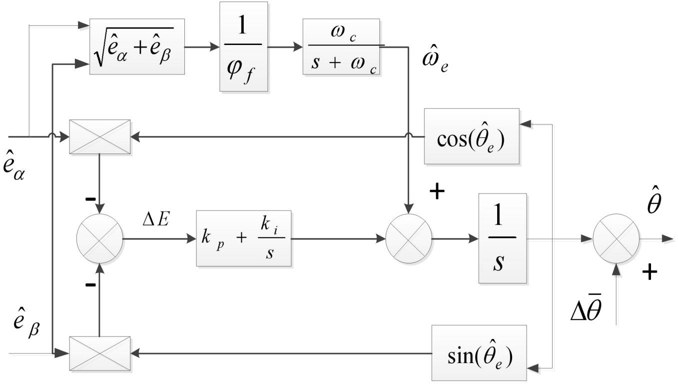


Fig. 2. Improved PLL flow diagram

By introducing a feed-forward path and subsequent rotor position compensation, the interference caused by static errors and low-pass filters is eliminated, thereby improving the accuracy of rotor speed and position estimation.

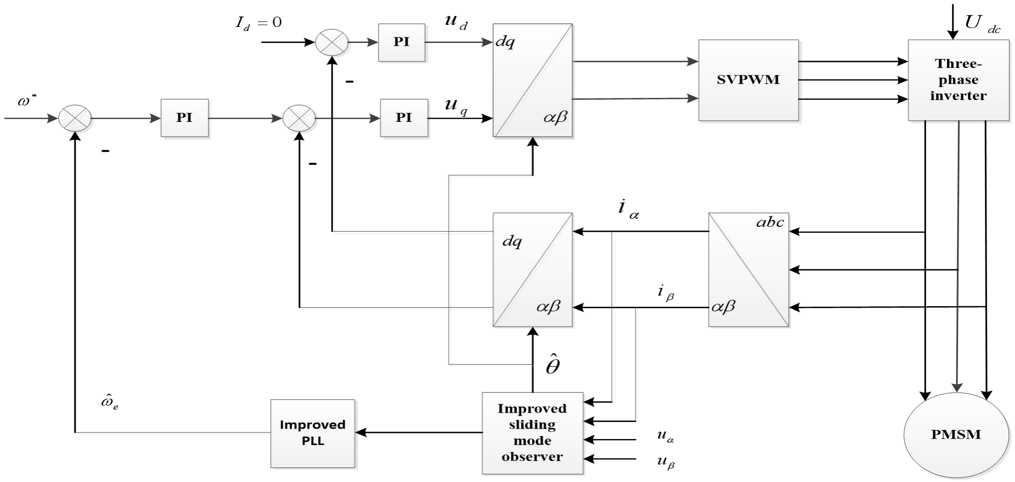


Fig. 3. Improved PLL flow diagram

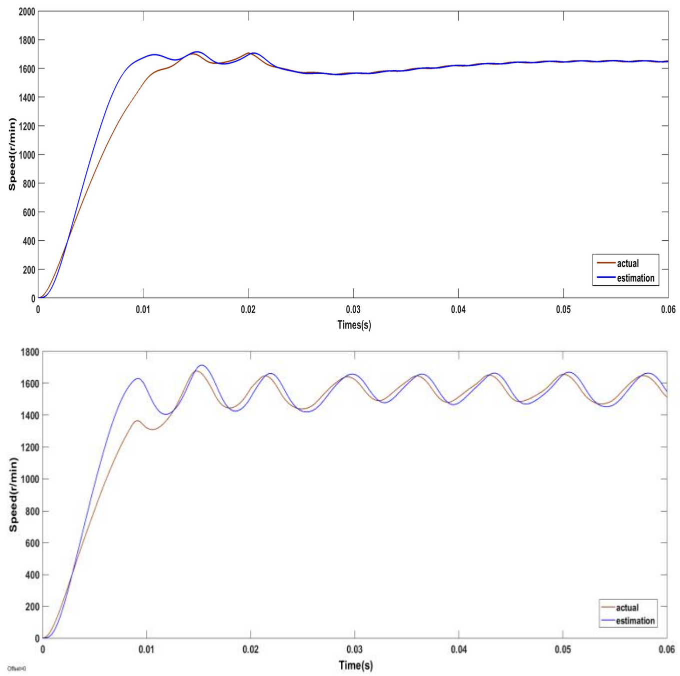
IV. SIMULATION ANALYSIS

To verify the effectiveness of the above design system, use Matlab simulation software for verification. The relevant parameters of the PMSM are shown in TABLE I .

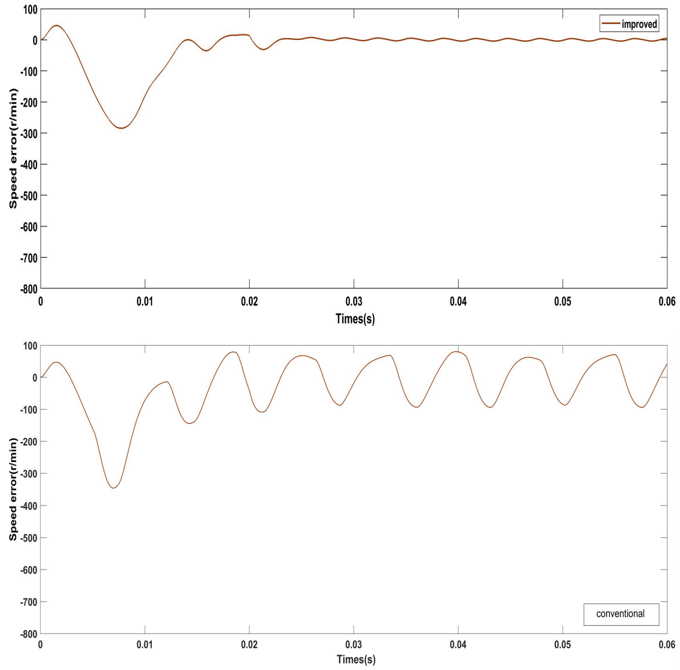
SMO's gain K=350. According to the above design, construct the sensor-less control system of PMSM(Fig. 3). To verify that the improved SMO can effectively suppress high-frequency resonance, compare the algorithm in this paper with the conventional SMO-PLL rotor position estimation method. As shown in Fig 4:

TABLE I. PMSM'S SIMULATION PARAMETERS

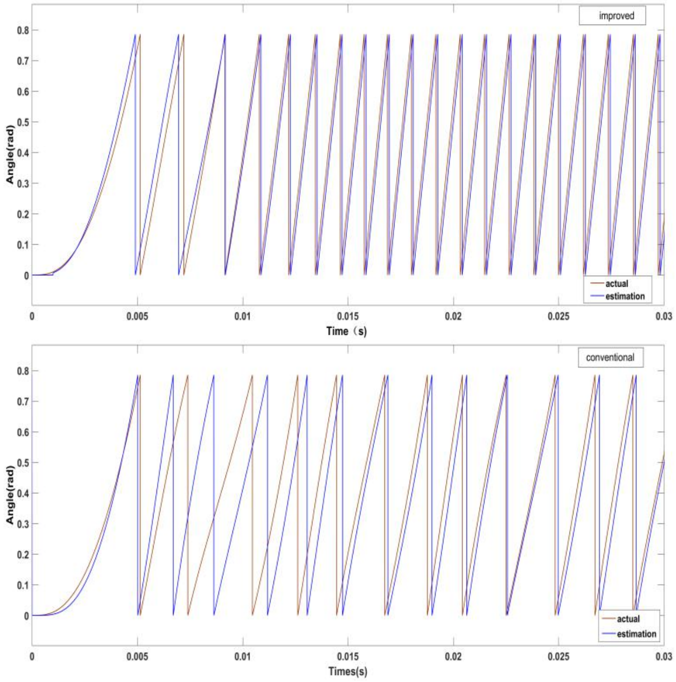
Iterms	Values
Inverter's DC bus voltage	$u_{dc} = 310V$
Pole pairs	P=4
Stator inductance	$L_s = 8.5mH$
Stator resistance	$R_s = 2.875\Omega$
Flux linkage	$\varphi_f = 0.175Wb$
Rotational inertia	$J = 0.001kg \cdot m^2$
Switching frequency	10 KHz



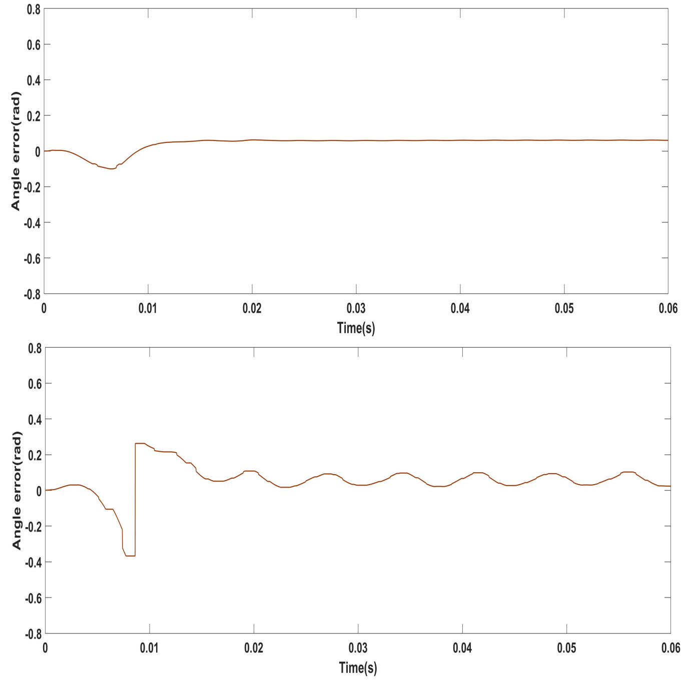
(a) Speed comparison of PMSM



(b) Comparison of speed error of PMSM



(c) Rotor position comparison



(d) Comparison of rotor position error

Fig. 4. Simulation comparison of the rotor position and speed of the system under the two methods

Fig . 4 (a) compares the image of the speed of the PMSM (improved above). From the image, we can see that the improved SMO is better than the conventional sliding film observation in terms of system chattering and tracking error. Fig. 4(b) is a comparison image of the speed error of the PMSM. The improved synovial observer is better than the conventional one. Fig. 4(c) and (d) is comparison image of the rotor position and error of the PMSM(improved above). The improved type is better than the conventional type in tracking.

V. CONCLUSION

The article proposes an improved SMO sensor-less control strategy for SMPMSM. This method uses a combination of SMO and back-EMF closed-loop feedback, which can effectively suppress the high-frequency chattering components existing in conventional SMO-PLL position detection methods, improve the dynamic response performance of the speed loop, and reduce the amount of code. The simulation results show that the control strategy in this paper is feasible.

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