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Research on Position-Sensorless Control of PMSM Based on ELO and NLESO-PLL

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Abstract: In the context of the position and speed information of the rotor being difficult to directly obtain in the position sensorless control of permanent magnet synchronous motors, this paper establishes a PMSM position sensorless vector control system model and designs a speed and position estimation structure consisting of an extended Luenberger observer and NLESO-PLL. This method first uses the extended Luenberger observer to estimate the motor's back electromotive force, and then estimates its components in the α and β coordinate systems from the stator voltage and current signals. Then, the estimated back electromotive force is input into NLESO-PLL, and the rotor position, angular velocity, and mechanical speed are estimated through nonlinear error feedback and the expansion state observation loop. Compared with the traditional PLL, NLESO-PLL can enhance dynamic tracking capability and anti-disturbance performance under conditions of sudden speed changes and load disturbances. Using MATLAB/Simulink, a PMSM position sensorless vector control simulation model is built, and speed step, load disturbance, and position estimation experiments are conducted under different operating conditions. The simulation results show that the proposed method can better track the actual speed and rotor position in the medium-to-high-speed operating range and maintain good estimation stability under speed changes and load disturbances, providing a feasible solution for position-sensorless control of PMSM at medium and high speeds.

Keywords: Permanent magnet synchronous motor; Position sensorless control; Extended Luenberger observer; Nonlinear extended state observer; Phase-locked loop

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1. Introduction

Permanent magnet synchronous motors offer high power density, high operating efficiency, fast torque response, and good speed regulation. They are widely used in electric vehicles, industrial servo systems, robots, and numerical control equipment. In high-performance vector control systems, rotor position and speed information are important bases for coordinate transformation, current decoupling control, and speed closed-loop regulation. Traditional control systems usually obtain rotor position information from encoders, rotary transformers, or Hall sensors. Still, mechanical sensors increase system cost and installation complexity and may reduce system reliability in high-temperature, vibration, dust, and strong electromagnetic interference environments. Therefore, the position-sensorless control method that estimates rotor position and speed from measurable signals, such as motor terminal voltage and current, has high research significance [1].

At present, the position sensorless control methods for permanent magnet synchronous motors mainly include the back electromotive force estimation method, the flux linkage observation method, the sliding mode observer method, the model reference adaptive method, the Kalman filter method, and the high-frequency signal injection method, etc. Among them, the back electromotive force-based methods utilize the back electromotive force information generated during the motor operation to estimate the rotor position. These methods have relatively clear structures, are easy to integrate with the motor mathematical model and vector control system, and are well-suited to the medium- and high-speed operating range [2]. In back electromotive force-based estimation methods, the extended Luenberger observer can uniformly observe the stator current and back electromotive force as extended states, and correct the state estimate through current-observation-error feedback [3]. It has the characteristics of a clear model form, a simple structure, and convenient engineering implementation. However, the observed reverse electromotive force still requires position extraction to determine the rotor angle and speed. The traditional phase-locked loop is simple in structure. Still, its dynamic response speed and anti-interference capability are easily affected by changes in speed, load disturbances, or fluctuations in reverse electromotive force estimation. This can lead to overshoot, lag, or steady-state fluctuations in the estimated speed. Especially when the motor operating state changes rapidly, it is difficult to achieve both speed tracking and smooth estimation simultaneously. Therefore, it is necessary to improve the back-end phase-locked loop structure by incorporating reverse electromotive force observations to enhance the dynamic performance and anti-interference capability of rotor position and speed estimation.

To address the aforementioned issues, this paper establishes a vector control system model for permanent magnet synchronous motors without position sensors. It employs an extended Luenberger observer to estimate the component of the reverse electromotive force in the two-phase stationary coordinate system. It combines this with a nonlinear expanded-state observer phase-locked loop to extract the rotor position and speed. This method uses the estimated reverse electromotive force output by the front-end extended Luenberger observer as input, constructs the phase-locked adjustment quantity via nonlinear error feedback, and compensates for disturbances and dynamic changes using the expanded state observer loop, thereby improving the estimation performance of the traditional PLL under variable-speed and disturbance conditions.

2. Mathematical model and control system of PMSM

To facilitate subsequent observer design, this paper selects the surface-mounted permanent magnet synchronous motor as the research object. Based on the equivalent circuit of the motor and under the condition of ignoring the effects of magnetic saturation, iron loss, and higher-order harmonics, the stator voltage equation of the PMSM can be established in the three-phase stationary coordinate system:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} \tag{1}$$

In the formula, u_a, u_b, u_c For the three–phase voltage of the stator, i_a, i_b, i_c For the three-phase current of the stator， R_S For stator phase resistance， ψ_a, ψ_b, ψ_c The three-phase stator flux components for surface-mounted permanent magnet synchronous motors are usually approximated. $L_d = L_q = L_s$. After the Clarke transformation, the three-phase stationary coordinate system can be converted into a two-phase stationary coordinate system. At this point, the stator voltage equation of the PMSM in the αβ coordinate system can be expressed as:

$$\begin{cases} u_\alpha = R_s i_\alpha + L_s \dfrac{di_\alpha}{dt} + e_\alpha \\ u_\beta = R_s i_\beta + L_s \dfrac{di_\beta}{dt} + e_\beta \end{cases} \tag{2}$$

Among them, u_a, u_b For the stator voltage components in the two-phase stationary coordinate system, i_a, i_b For the stator current component; e_a, e_b For the anti-electromotive force component. The relationship between the reverse electromotive force and the rotor position and rotational speed is:

$$\begin{cases} e_\alpha = -\omega_e \psi_f \sin\theta_e \\ e_\beta = \omega_e \psi_f \cos\theta_e \end{cases} \tag{3}$$

The component of the reverse electromotive force contains information about the rotor position and speed, so it is possible to obtain this information through the analysis of e_a, e_b The estimation is obtained indirectly to determine the rotor state. To facilitate the subsequent expansion of the design of the Longberg observer, Equation (2-2) is rewritten as the current state equation:

$$\begin{cases} \dfrac{di_\alpha}{dt} = -\dfrac{R_s}{L_s} i_\alpha - \dfrac{1}{L_s} e_\alpha + \dfrac{1}{L_s} u_\alpha \\ \dfrac{di_\beta}{dt} = -\dfrac{R_s}{L_s} i_\beta - \dfrac{1}{L_s} e_\beta + \dfrac{1}{L_s} u_\beta \end{cases} \tag{4}$$

3. PMSM position sensorless observer

3.1. Basic principles of the Loberg observer

In the motor control system, not all state quantities can be directly measured by sensors. To obtain the system's internal state from limited measurable signals, a state observer is usually required. The Luenberger observer is a state-estimation method based on the system's state-space model [3]. Its core idea is to dynamically reconstruct the unmeasurable state by using the system input, measurable output, and output estimation error. For general linear systems, their state space expression can be written as:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{5}$$

In the formula, *x*. As a system state variable, *u*. For system input, *y*. For system output, *A,B,C*. They are, respectively, the state matrix, the input matrix, and the output matrix. When the system status *x* When it is not possible to measure everything directly, the following form of Lorch observer can be constructed;

$$\begin{cases} \dot{\hat{x}} = Ax + Bu + L(y - y) \\ \hat{y} = Cx \end{cases} \tag{6}$$

In the formula, $\hat{x}$ For the estimated values of the state $\hat{y}$ To output the estimated value, L, for the observer gain matrix, $y - \hat{y}$ To output the observation error. Compared with the original system model, the Lorchberg observer incorporates an error feedback term. $L(y - \hat{y})$ This method can continuously correct state estimates based on the deviation between actual and estimated outputs, thereby improving state estimation accuracy.

Define the state estimation error as:

$$\tilde{x} = x - \hat{x} \tag{7}$$

The observable error dynamic equation can be obtained:

$$\dot{\tilde{x}} = (A - LC)\tilde{x} \tag{8}$$

From Equation (3-4), it can be seen that the error convergence performance of the observer is mainly determined by the eigenvalues of the matrix A - LC. By reasonably selecting the observer gain matrix L, the error system can be made stable, and the estimated state can gradually converge to the vicinity of the actual state. Therefore, the Lorchberger observer has the advantages of a clear structure, clear physical meaning, and ease of engineering implementation.

3.2. Extension of the basic principles of the Lorenz observer

In position-independent sensorless control of a PMSM, the rotor position and speed information are contained in the back electromotive force. Still, the back electromotive force cannot be measured directly. Therefore, the back electromotive force can be regarded as an extended state, and together with the stator current, it constitutes the extended state variables:

$$x = \begin{bmatrix} i_\alpha & i_\beta & e_\alpha & e_\beta \end{bmatrix}^T \tag{9}$$

The input variables and output variables are selected as follows:

$$u = \begin{bmatrix} u_\alpha & u_\beta \end{bmatrix}^T, \quad y = \begin{bmatrix} i_\alpha & i_\beta \end{bmatrix}^T \tag{10}$$

By combining the voltage equation of PMSM in the two-phase stationary coordinate system and the dynamic relationship of the back electromotive force, the extended state equation can be obtained:

$$\begin{cases} \dfrac{di_\alpha}{dt} = -\dfrac{R_s}{L_s} i_\alpha - \dfrac{1}{L_s} e_\alpha + \dfrac{1}{L_s} u_\alpha \\ \dfrac{di_\beta}{dt} = -\dfrac{R_s}{L_s} i_\beta - \dfrac{1}{L_s} e_\beta + \dfrac{1}{L_s} u_\beta \\ \dfrac{de_\alpha}{dt} = -\omega_e e_\beta \\ \dfrac{de_\beta}{dt} = \omega_e e_\alpha \end{cases} \tag{11}$$

When expressing Equation (3-7) in matrix form, the system matrix can be represented as:

$$A=\begin{bmatrix} -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} & 0 \\ 0 & -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} \\ 0 & 0 & 0 & -\omega_e \\ 0 & 0 & \omega_e & 0 \end{bmatrix} \tag{12}$$

$$B=\begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad C=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{13}$$

Based on the above extended state model, an extended Luenberger observer for PMSM can be constructed. Let the state variables of the observer be:

$$\hat{x}=\begin{bmatrix} \hat{i}_\alpha & i_\beta & e_\alpha & e_\beta \end{bmatrix}^T \tag{14}$$

Then the specific expression of the observer is:

$$\begin{cases} \frac{d\hat{i}_\alpha}{dt}=-\frac{R_s}{L_s}\hat{i}_\alpha-\frac{1}{L_s}\hat{e}_\alpha+\frac{1}{L_s}u_\alpha+k_i(i_\alpha-i_\alpha) \\ \frac{d\hat{i}_\beta}{dt}=-\frac{R_s}{L_s}\hat{i}_\beta-\frac{1}{L_s}\hat{e}_\beta+\frac{1}{L_s}u_\beta+k_i(i_\beta-i_\beta) \\ \frac{d\hat{e}_\alpha}{dt}=-\hat{\omega}_e\hat{e}_\beta+k_e(i_\alpha-\hat{i}_\alpha) \\ \frac{d\hat{e}_\beta}{dt}=\hat{\omega}_e\hat{e}_\alpha+k_e(i_\beta-\hat{i}_\beta) \end{cases} \tag{15}$$

In the formula, $\hat{i}a, i_b$ As an estimate of the stator current. $\hat{e}_a, e_b$ For the estimated value of the reverse electromotive force ki As the feedback gain for the current error ke. For the feedback gain of the anti-electromotive force error, in this paper, the extended Luenberger observer adopts a fixed gain structure, and the simulation parameters are taken as ki=1000 、 ke=10000 . Due to the actual angular electric velocity ω_e It is difficult to obtain directly. In the observer, the estimated angular velocity is used. $\hat{\omega}_e$ Participate in the dynamic calculation of the reverse electromotive force. See **Figure 1**.

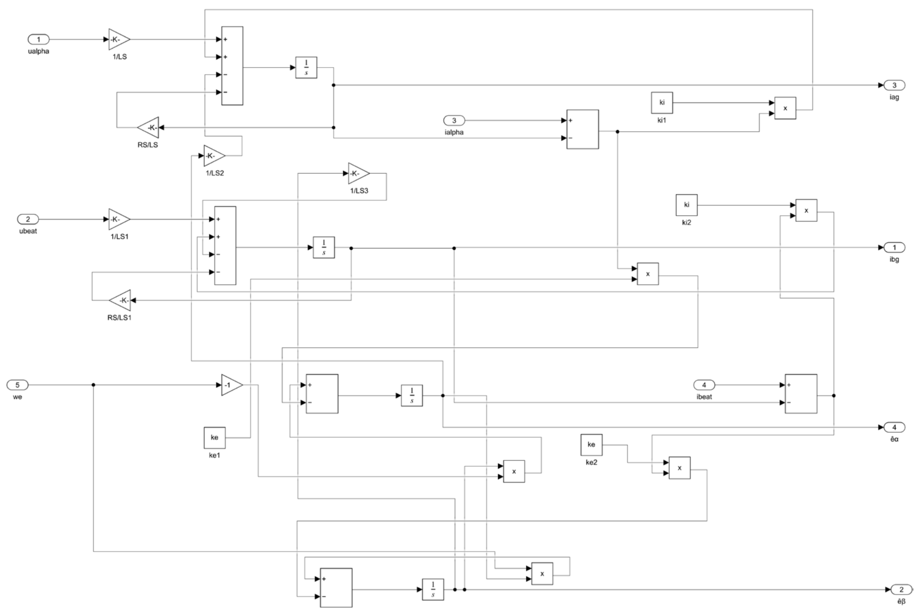

Figure 1. Extended Loberg observer simulation model.

4. Position and speed extraction method based on NLESO-PLL

4.1. Principle of traditional PLL (Phase-Locked Loop)

In the PMSM position-sensorless control system, the extended Luenberger observer can estimate the armature-voltage component in the two-phase stationary coordinate system. However, the armature voltage itself cannot directly serve as the rotor position and speed signals required for vector control. Therefore, an additional position-extraction section needs to be designed to extract the rotor position angle and speed from the estimated armature-voltage component. The phase-locked loop is simple in structure, easy to implement, and a widely used method for extracting the armature voltage position in a PMSM. According to the relationship of the PMSM armature voltage, the estimated armature voltage can be expressed as:

$$\begin{cases} \hat{e}_\alpha = -\hat{\omega}_e \psi_f \sin \hat{\theta}_e \\ \hat{e}_\beta = \hat{\omega}_e \psi_f \cos \hat{\theta}_e \end{cases} \tag{16}$$

A traditional PLL typically constructs the phase error signal based on the estimated reverse electromotive force:

$$\varepsilon = -\hat{e}_\alpha \cos \hat{\theta}_e - e_\beta \sin \theta_e \tag{17}$$

When the estimated angle matches the actual rotor angle, the phase-locked error approaches zero; when there is a deviation between the two, the regulator corrects the error signal to estimate the angular velocity, and the estimated position angle is obtained by integrating the estimated angular velocity. The traditional PI-type PLL can be expressed as:

$$\begin{cases} \dot{\xi} = \varepsilon \\ \hat{\omega}_e = K_p \varepsilon + K_i \xi \\ \dot{\hat{\theta}}_e = \hat{\omega}_e \end{cases} \tag{18}$$

In the formula, K¬_P and K_i represent the proportional and integral coefficients of the PLL, and ξ is the error integral term. The traditional PLL structure is relatively simple, but its dynamic performance mainly depends on the PI parameters. When the motor experiences sudden changes in speed or load, fixed PI parameters struggle to achieve both fast tracking and stable smoothness simultaneously. This often leads to problems such as speed estimation lag, overshoot, or increased fluctuations.

4.2. NLESO-PLL design

To enhance the tracking capability and anti-disturbance performance of the position and speed extraction section under dynamic conditions, this paper introduces a nonlinear expanded state observation approach based on the traditional PLL and constructs NLESO-PLL [4]. This design draws on ADRC's extended-state disturbance estimation idea and adaptive NLESO-based PMSM sensorless speed-control research [5]. Recent ESO-based PLL sensorless-control research also provides a comparable implementation reference [6]. Reviews of PMSM position-sensorless control technology also identify observer-based compensation and PLL-based extraction as common technical routes [7]. This method uses the reverse electromotive force estimated by the front-end extended Luenberger observer as the input, and the phase-locked error is still constructed using Equation (4-2). To mitigate the significant impact of fluctuations in the estimated reverse electromotive force on the phase-locked loop, amplitude limiting or filtering can be applied to the error signal in the actual implementation, thereby yielding the error input for the NLESO-PLL. The state equation of NLESO-PLL in this paper is designed as $\hat{e}_{\hat{a}}$,e

$$\begin{cases} \dot{\hat{\theta}}_e = \hat{\omega}_e + \beta_1 fal(\varepsilon) \\ \dot{\hat{\omega}}_e = \hat{z} + \beta_2 fal(\varepsilon) \\ \dot{\hat{z}} = \beta_3 fal(\varepsilon) - \lambda_z z \end{cases} \tag{19}$$

In the formula,To estimate the rotor electrical angle,To estimate the angular velocity of electricity,To expand the state estimator, it is used to characterize the comprehensive disturbance and dynamic compensation terms during the phaselocking process. For the observer's gain,To expand the state attenuation coefficient. The NLESO-PLL not only utilizes the phase-locked error to correct the position and velocity estimation, but also introduces the expanded state to compensate for the effects caused by velocity jumps, load disturbances, and fluctuations in the estimated back electromotive force. Compared with the traditional PI-type PLL, this structure can enhance the dynamic regulation capability and reduce the estimation fluctuations under the influence of disturbances. $\hat{\theta}_e \hat{\omega}_e \hat{z} \beta_1, \beta_2, \beta_3 \lambda_z$

The nonlinear error-feedback function in NLESO-PLL is employed. fal Function is defined as:

$$fal(\varepsilon, \alpha, \delta) = \begin{cases} \dfrac{\varepsilon}{\delta^{1-\alpha}}, & |\varepsilon| \leq \delta \\ |\varepsilon|^{\alpha} sign(\varepsilon), & |\varepsilon| > \delta \end{cases} \tag{20}$$

In the formula, fal(.) is the nonlinear feedback function, alpha is the nonlinear factor, and delta is the width of the linear interval. When the error is relatively small, the function is approximately linear, which helps reduce steady-state jitter; when the error is large, the function shows nonlinear feedback characteristics and improves dynamic correction. After this function is introduced into the PLL structure, NLESO-PLL can improve tracking performance under dynamic speed variation and load disturbance. α.δfalfalfal

Output ù e Estimated angular electric speed. To obtain the mechanical speed, use the relationship between the electrical angular speed and the mechanical speed. Conduct the conversion:

$$\hat{n}_{rpm} = \frac{60}{2\pi p_n}\hat{\omega}_e \tag{21}$$

In the formula, pn represents the number of pole pairs of the motor. $\hat{n}_{rpm}$ To estimate the rotational speed of the machine, use r/min.

In conclusion, the position and speed estimation process adopted in this paper is as follows: First, the extended Luenberger observer estimates the armature reaction voltage component from the stator voltage and current signals. $\hat{e}_{\text{â}}, \hat{e}$ Then, NLESO-PLL constructs the phase-locked error based on the estimated rotor flux vector; finally, the estimated position is obtained through the nonlinear extended state observation structure. $\hat{\theta}_{\text{e}}$ 、 Estimate the angular electric velocity $\hat{\omega}_{\text{e}}$ And estimating the rotational speed of the machinery $\hat{n}_{\text{rpm}}$. See **Figures 2** and **3**.

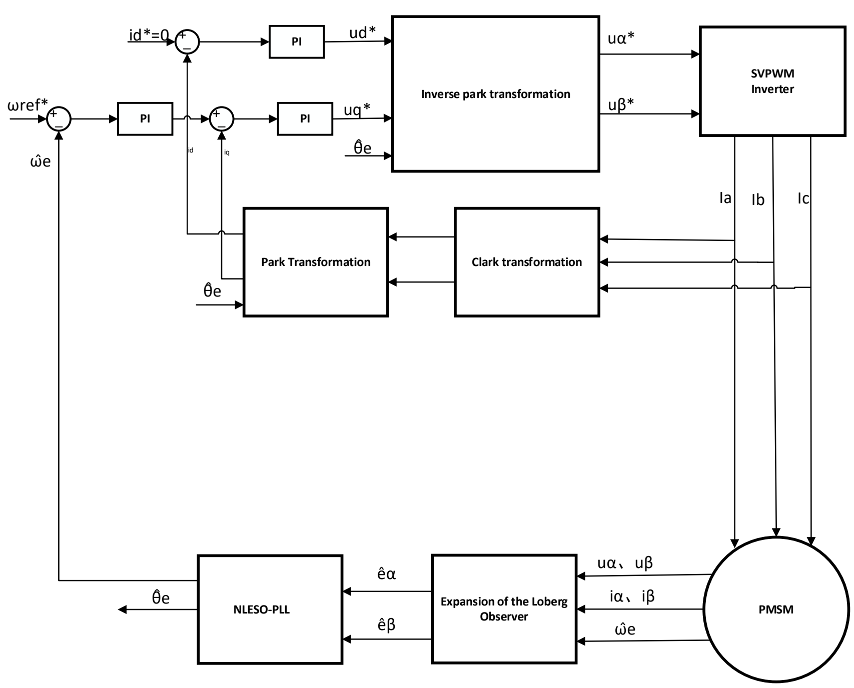

Figure 2. Structure diagram of PMSM position sensorless control system based on ELO and NLESO-PLL.

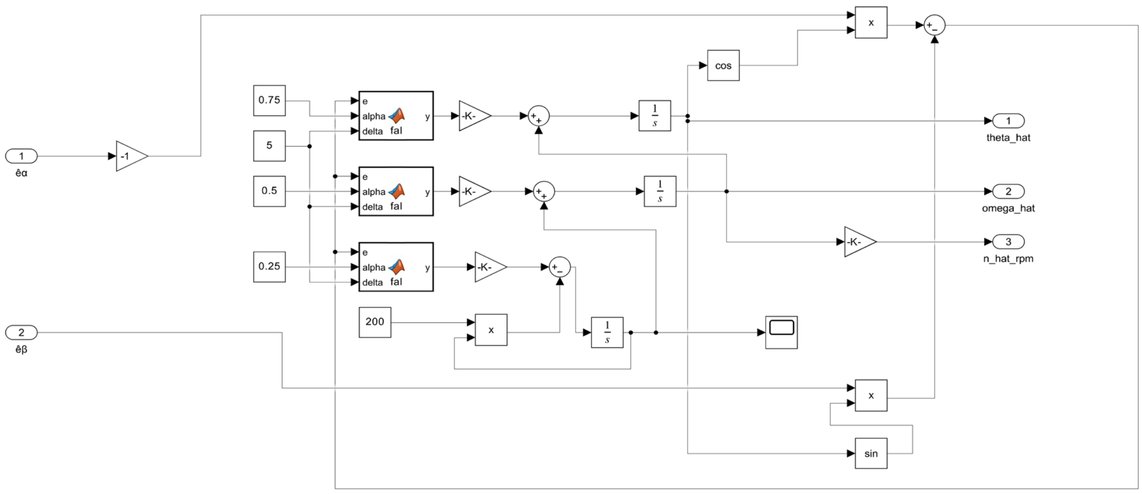

Figure 3. Simulation model of the NLESO-PLL structure.

5. Simulation results and analysis

5.1. Simulation model and parameter settings

To verify the effectiveness of the extended Lorch observer and the NLESO-PLL position- and speed-extraction method proposed in this paper, a PMSM position-sensorless vector-control simulation model was built in MATLAB/Simulink. The system uses the extended Lorch observer as the front-end back-electromotive-force observation link and outputs the estimated back electromotive force, following the same observer-based modeling direction as adaptive Luenberger-observer schemes [8]. The backend uses NLESO–PLL to extract the position and speed of the reverse electromotive force, and outputs the estimated rotor position.Estimate the electrical angular velocity. And estimate the mechanical rotational speed.. $\hat{e}_\alpha,\hat{e}_\beta\hat{\theta}_e\hat{\omega}_e\hat{n}_{rpm}$

This paper presents a comprehensive test that combines speed step and load disturbance. The simulation duration is set to 10 seconds. The given rotational speeds are 700 r/min, 1500 r/min, 2500 r/min, and -500 r/min, and a T = 6 N.m operation is applied at 3.5 seconds. The load is reduced to T = 3 N·m at 6.5 seconds to verify the proposed method's estimation performance under medium-to-high-speed shifting and disturbance conditions.

5.2. Comprehensive test of speed and load

Figure 4 presents the comparison results of the actual rotational speed and the observed rotational speed under the combined conditions of speed step and load disturbance.

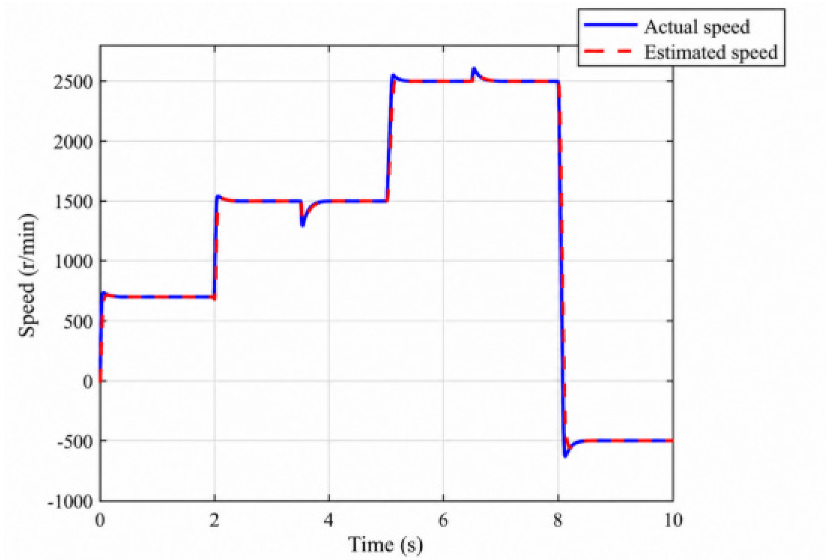

Figure 4. Comprehensive test results of speed step change and load disturbance.

As shown in **Figure 4**, under the operating conditions of 700 r/min, 1500 r/min, 2500 r/min, and -500 r/min, the observed speed closely tracks the actual speed, and the overall trend is consistent. When the given speed changes, the estimated speed dynamically adjusts to the actual speed and reaches a stable state after a brief transition. This result indicates that the extended Lorchberg observer can provide an effective estimate of the back electromotive force for the rear-end phase-locked loop, and the NLESO-PLL can extract speed from this information, which is consistent with improved PLL-based position and speed extraction methods [9].

To further examine the dynamic tracking effect during speed variation, a detailed analysis was conducted of the speed-step stage in the comprehensive test. **Figure 5** presents the rotational speed response curve during the speed step stage.

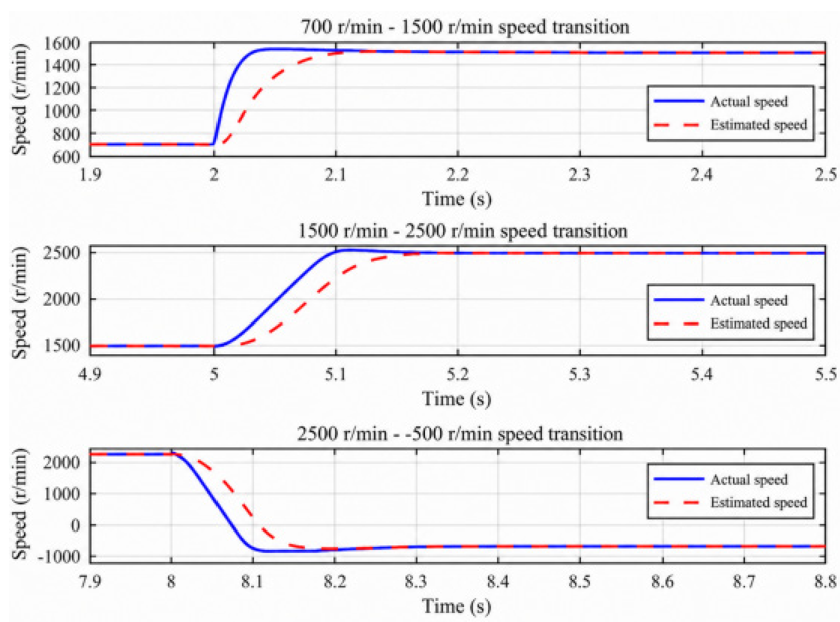

Figure 5. Local plot of rotational speed response during the speed step-up stage.

As shown in **Figure 5**, when the rotational speed is changed from 700 r/min to 1500 r/min and then to 2500 r/min, it reaches a steady state within approximately 0.1–0.2 seconds. The observed rotational speed can quickly follow changes in the actual rotational speed, and no obvious divergence occurred during the dynamic process. When the motor is switched from forward to reverse at -500 r/min, the observed rotational speed completes the direction change within 0.1–0.2 seconds. Due to significant changes in operating state during reverse switching, the estimation results may briefly fluctuate but will subsequently converge again. This indicates that the proposed method has good dynamic tracking performance under sudden speed changes.

To verify the anti-disturbance performance of the proposed method, load disturbances were applied near the 3.5-second and 6.5-second steady-state points, and a local amplification analysis was conducted during the disturbance stage. **Figure 6** presents the speed response curve during the load disturbance stage.

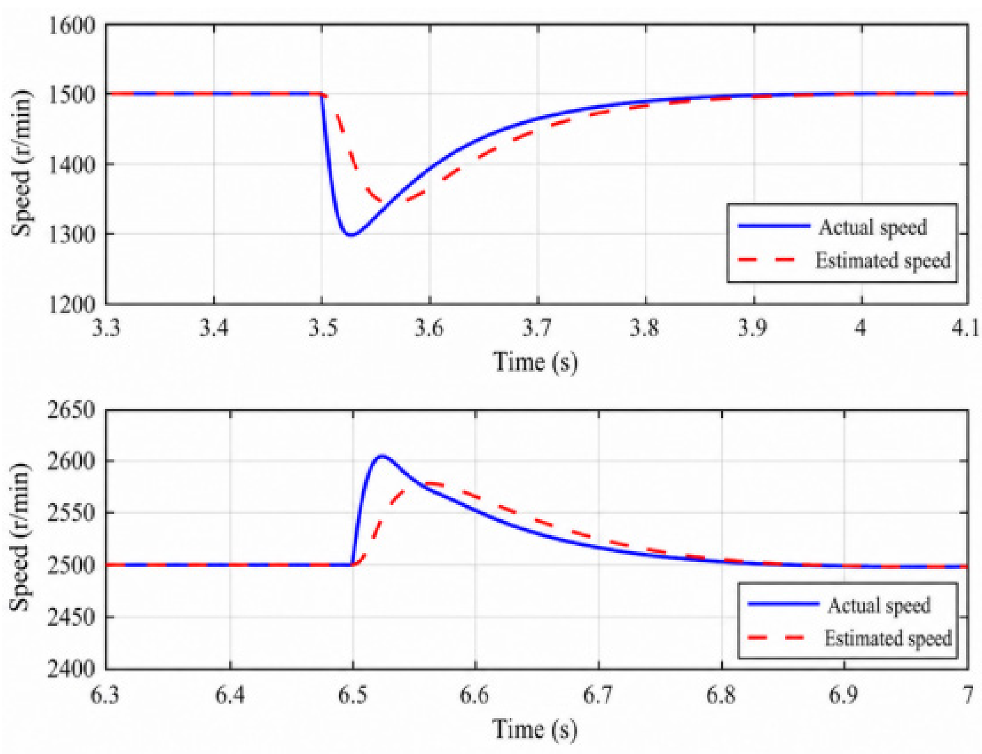

Figure 6. Local plot of rotational speed response during the load disturbance stage.

As shown in **Figure 6**, after the load disturbance is applied, the actual speed shows a short-term fluctuation, and the observed speed changes accordingly. It takes approximately 0.3 to 0.4 seconds to re-track the actual speed. The expanded state in NLESO-PLL can play a certain compensatory role in the dynamic changes caused by the disturbance, preventing the estimated speed from continuously deviating or experiencing significant oscillations; this disturbance-compensation idea is also reflected in LESO phase-lead correction research [10]. This result indicates that the proposed method has good estimation stability and anti-disturbance capability under medium- and high-speed load-disturbance conditions.

To verify the effectiveness of the position estimation, four typical rotational speed points of 700 r/min, 1500 r/min, 2500 r/min, and -500 r/min were selected, and the actual rotor position and the estimated rotor position were compared. **Figure 7** shows the positions at different rotational speed points. Estimated result:

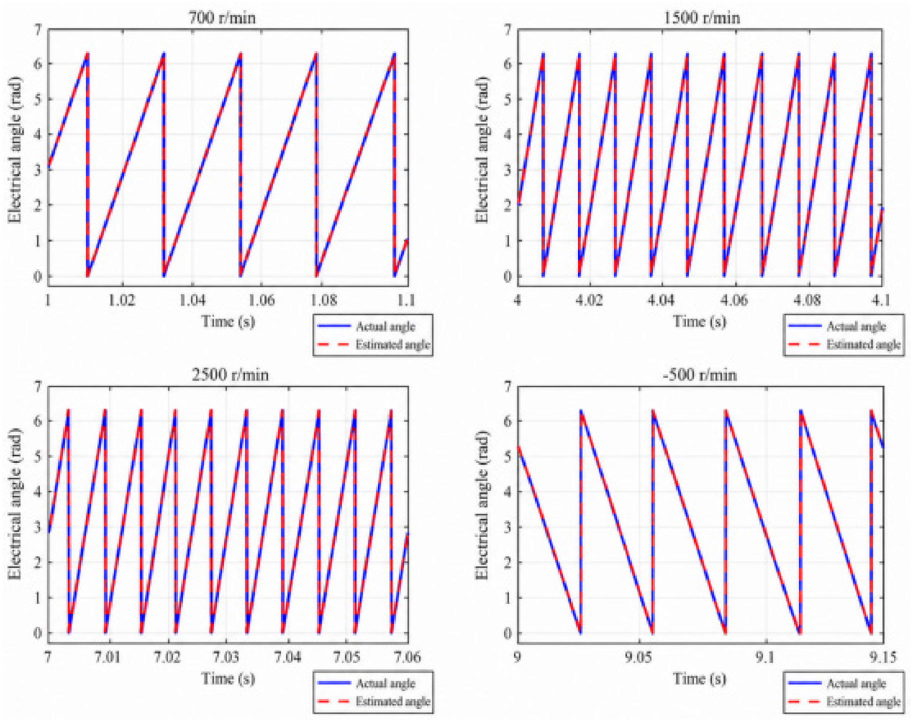

Figure 7. Comparison of rotor positions at different rotational speeds.

As shown in **Figure 7**, under both forward and reverse operating conditions, the estimated position closely follows the actual rotor position, and the two exhibit essentially the same trend.

6. Conclusion

This paper extends the application of the Longberg observer and NLESO-PLL to the position-sensorless vector control system for permanent magnet synchronous motors. Based on MATLAB/Simulink, a simulation model for PMSM position sensorless control was built. The simulation results show that the proposed method effectively achieves speed tracking and rotor position estimation under varying operating conditions, including different speeds and loads. During speed step changes and load disturbances, the observed speed can follow the actual speed changes, and the estimation results are overall stable. The extended Longberg observer can effectively estimate the armature reaction voltage component. At the same time, NLESO-PLL can extract the rotor position and speed from the armature reaction voltage information, thereby improving the system's estimation stability under dynamic changes and disturbances. Overall, the ELO + NLESO-PLL method adopted in this paper is suitable for high-speed, position-sensorless control of PMSMs and can serve as a reference for designing position-sensorless control strategies for permanent magnet synchronous motors.

Disclosure statement

The authors declare no conflict of interest.

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