

Enhanced Position Estimation of PMSM Using the Luenberger Observer and PLL Algorithm: Design and Simulation Study

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ABSTRACT

This study proposes an enhanced method for estimating the position of a permanent magnet synchronous motor (PMSM) using the Luenberger observer and phase-locked loop (PLL) algorithm. The main contribution to this research is the use of two low-pass filters (LPF) at the input of the PLL, which results in softer position reconstruction compared with conventional PLL. The proposed method is designed and simulated using the MATLAB/Simulink platform. The performance of the proposed method was evaluated and compared with conventional PLL and PLL with one LPF using several performance metrics such as estimation accuracy, convergence time, and stability. Simulation results show that the proposed method achieves better estimation accuracy and higher stability compared with the other methods. Additionally, the proposed method is robust to various disturbances such as load torque and parameter variations. Overall, the proposed method offers an effective and efficient solution for estimating the position of PMSM in various industrial applications.

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1. INTRODUCTION

Accurate estimation of the permanent magnet synchronous motors (PMSMs) position plays a crucial role in various industrial applications, ranging from robotics to electric vehicle propulsion systems [1]–[6]. Accurate determination of the rotor position allows for precise control and improved overall performance of these motor systems. In recent years, numerous techniques to estimate the position have been developed and used to enhance the accuracy and robustness of PMSM control [7], [8].

The conventional phase-locked loop (PLL) algorithm has been widely used for estimating the position of PMSMs due to its simplicity and effectiveness. However, it suffers from certain limitations, such as sensitivity to noise and disturbances, which can affect its performance and stability [9].

To overcome these limitations, El Murr *et al.* [10] incorporated low-pass filters (LPF) at the input of the PLL structure to avoid any disturbance that affects the demodulation and detection process. These LPFs play a crucial role in smoothing the input signal, resulting in more accurate and reliable position reconstruction. By mitigating

the adverse effects of noise and disturbances, the proposed method offers softer position estimation, leading to enhanced overall system performance.

This study focuses on the enhanced estimation of the PMSMs position using a combination of the Luenberger observer [8] and the PLL algorithm [11]. The novel aspect of this research lies in the incorporation of an LPF at the input of the PLL, leading to a smoother back-electromotive force (back-EMF) waveform and, consequently, a more accurate and improved response [12], [13].

The study of enhanced estimation of the PMSMs position has attracted significant interest from researchers. WU *et al.* [8] proposed an optimized phase-locked loop based on the Levenberg–Marquardt (LM) algorithm to improve the estimation accuracy of the sliding mode observer-based position estimator. The estimation of position suffers from DC bias caused by digital control delay and harmonics caused by inverter nonlinearity and flux spatial harmonics. Xiao *et al.* [14] published a study in 2020 on high-frequency signal injection methods for sensorless control of PMSM drives. However, the acoustic noise and torque ripples

caused by the injected high-frequency signal limit the application of these methods.

The LPF serves as a preprocessing stage in the position estimation algorithm, filtering out high-frequency noise and disturbances in the back-EMF signal [15]. By using this LPF, the PLL can operate on a cleaner and more reliable input, resulting in enhanced estimation accuracy and performance. This approach offers a significant advantage over conventional PLL-based position estimation methods, which often suffer from noise sensitivity and distortions in the back-EMF signal [16].

In this study, comprehensive simulations were conducted using the MATLAB/Simulink platform to evaluate the performance and effectiveness of the proposed enhanced position estimation technique. A comparative analysis was conducted between the proposed method and conventional PLL-based approaches, considering key metrics such as estimation accuracy, convergence time, and stability. The results obtained from the simulations demonstrate the superiority of the proposed method. The incorporation of the LPF in the input of the PLL leads to a smoother back-EMF waveform, significantly reducing the impact of noise and disturbances on the position estimation process. Consequently, the enhanced position estimation technique achieves higher accuracy, faster convergence time, and improved stability, making it an attractive solution for real-world applications in motor control and industrial automation.

2. PMSM AND LUENBERGER OBSERVER MATHEMATICAL MODEL

It is crucial to obtain the state-space model of the PMSM for the implementation of the Luenberger observer [6], [8], [17]. The state-space model represents the dynamic behavior of the PMSM system in terms of its internal states and inputs. By using the state-space model, the Luenberger observer can estimate the unmeasurable states of the PMSM, such as rotor position and current, based on the available measured outputs. International Journal of Advances in Engineering & Technology, the mathematical model of the PMSM can be written as shown in (1) [6]:

$$\begin{cases} \frac{di_\alpha}{dt} = -\frac{R}{L}i_\alpha + \frac{1}{L}[v_\alpha - e_\alpha] \\ \frac{di_\beta}{dt} = -\frac{R}{L}i_\beta + \frac{1}{L}[v_\beta - e_\beta] \end{cases} \quad (1)$$

where R is the machine's resistance, L is the machine's inductance, i_α and i_β are the currents, v_α and v_β are the voltages, and e_α and e_β are the back-EMF forces in the α - β reference frame. The back-EMF can be written as shown in (2):

$$\begin{cases} e_\alpha = -\omega_r \lambda_e \sin(\theta_r) \\ e_\beta = \omega_r \lambda_e \cos(\theta_r) \end{cases} \quad (2)$$

The derivative of (2) can be expressed as shown in (3):

$$\begin{cases} \frac{de_\alpha}{dt} = -\omega_r e_\beta \\ \frac{de_\beta}{dt} = \omega_r e_\alpha \end{cases} \quad (3)$$

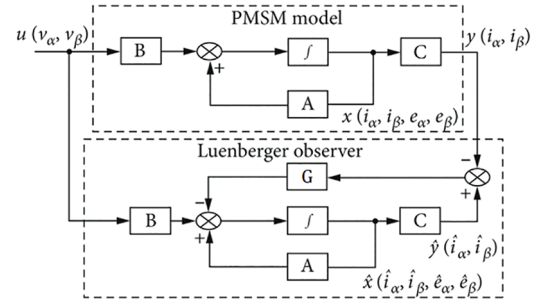


Fig. 1. State-space block diagram model of PMSM and the Luenberger observer.

The state-space model of the PMSM in the α - β reference, considering (1) and (3), can be written as shown in (4):

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (4)$$

where:

$$A = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ 0 & 0 \end{bmatrix}; B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}; C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$x = [i_\alpha, i_\beta, e_\alpha, e_\beta]^T; u = [v_\alpha, v_\beta]^T; y = [i_\alpha, i_\beta]^T$$

Based on Luo *et al.* [6] and Xia [18], the Luenberger observer formula can be written as shown in (5):

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + G(y - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \quad (5)$$

where $\hat{x}$ and $\hat{y}$ denote the estimated variables, and G is the observer input vector, which can be written as shown in (6):

$$G = \begin{bmatrix} g_i \\ g_e \end{bmatrix} \quad (6)$$

where:

g_i is the current observer gain,

g_e is the back-EMF observer gain.

Fig. 1 shows the representation of the Luenberger observer model and the state-space model of the PMSM [6].

Based on (1), (3), (5), and (6), we can obtain the full model of the Luenberger observer for the PMSM machine:

$$\begin{cases} \frac{d\hat{i}_\alpha}{dt} = -\frac{R}{L}\hat{i}_\alpha + \frac{1}{L}v_\alpha - \frac{1}{L}\hat{e}_\alpha + g_i(i_\alpha - \hat{i}_\alpha) \\ \frac{d\hat{i}_\beta}{dt} = -\frac{R}{L}\hat{i}_\beta + \frac{1}{L}v_\beta - \frac{1}{L}\hat{e}_\beta + g_i(i_\beta - \hat{i}_\beta) \\ \frac{d\hat{e}_\alpha}{dt} = -\omega_r\hat{e}_\beta + g_e(i_\alpha - \hat{i}_\alpha) \\ \frac{d\hat{e}_\beta}{dt} = \omega_r\hat{e}_\alpha + g_e(i_\beta - \hat{i}_\beta) \end{cases} \quad (7)$$

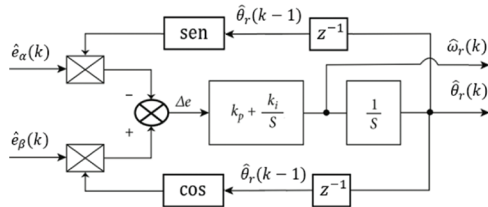


Fig. 2. Conventional PLL observer.

Discretizing (7) by the sample time T_s becomes:

$$\begin{cases} \hat{i}_\alpha(k+1) = \hat{i}_\alpha(k) - T_s \frac{R}{L} i_\alpha(k) + \frac{T_s}{L} v_\alpha - \frac{T_s}{L} \hat{e}_\alpha(k) \\ \quad + T_s g_i [i_\alpha(k) - \hat{i}_\alpha(k)] \\ \hat{i}_\beta(k+1) = \hat{i}_\beta(k) - T_s \frac{R}{L} i_\beta(k) + \frac{T_s}{L} v_\beta - \frac{T_s}{L} \hat{e}_\beta(k) \\ \quad + T_s g_i [i_\beta(k) - \hat{i}_\beta(k)] \\ \hat{e}_\alpha(k+1) = \hat{e}_\alpha(k) - T_s \omega_r \hat{e}_\beta(k) + T_s g_e [i_\alpha(k) - \hat{i}_\alpha(k)] \\ \hat{e}_\beta(k+1) = \hat{e}_\beta(k) + T_s \omega_r \hat{e}_\alpha(k) + T_s g_e [i_\beta(k) - \hat{i}_\beta(k)] \end{cases} \quad (8)$$

After estimating the back-EMF based on the estimated current and the back-EMF observer gain, the rotor position can be estimated using the arctangent of the counter back-EMF, as shown in (9):

$$\hat{\theta}_r = \tan^{-1} \left(-\frac{\hat{e}_\alpha(k+1)}{\hat{e}_\beta(k+1)} \right) \quad (9)$$

where $\hat{\theta}_r$ is the estimated electrical rotor angle.

According to (8), the arctangent function is used to calculate the electrical angle of the rotor. In practice, there are many harmonics and noises in the control system due to the nonlinearity of the inverter that drives the PMSM [6]. Therefore, the use of the arctangent function introduces a higher estimation error in the position and velocity of the rotor. Another method for estimating the rotor position and velocity uses PLL, which, together with the Luenberger observer, effectively avoids the noise caused by the arctangent function [19].

3. CONVENTIONAL PLL-BASED ESTIMATOR

The PLL estimator for PMSM is a technique used to estimate the rotor position and velocity of the motor without the need for direct position sensors. The PLL estimator leverages the principles of phase and frequency synchronization to estimate the rotor position based on the back-EMF signal of the motor [9], [19].

The basic idea behind the PLL observer is to compare the phase of the back-EMF signal from the Luenberger observer with a reference signal that is internally generated. This reference signal is typically derived from the estimated rotor angle using sine and cosine functions. By adjusting the phase and frequency of the reference signal, the observer aims to align it with the phase of the back-EMF signal. The Fig. 2 shows the conventional PLL observer.

To achieve this alignment, a closed-loop system is used. The difference between the phase of the back-EMF signal

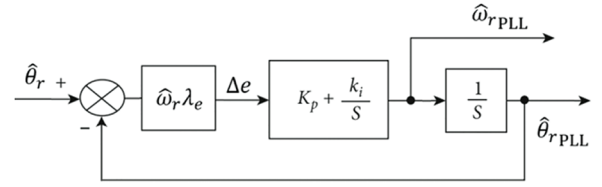


Fig. 3. Simplified PLL observer.

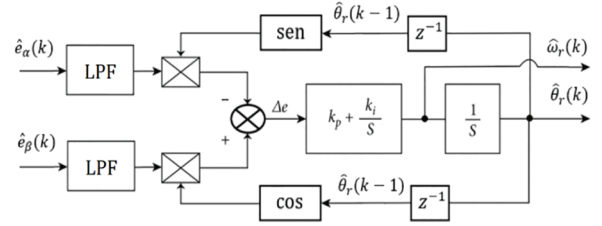


Fig. 4. Enhanced PLL observer.

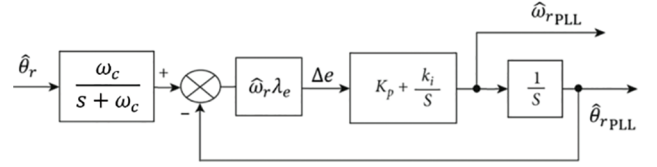


Fig. 5. Simplified enhanced PLL observer.

and the reference signal is fed into a proportional integral (PI) controller, which adjusts the frequency and phase of the reference signal. The output of the PI controller is the estimated angular frequency that is integrated to generate the estimated rotor electrical angle. Hence, the estimated rotor angle is multiplied by sine and cosine functions to generate the reference signal.

By continuously adjusting the phase and frequency of the reference signal based on the phase difference between the back-EMF and reference signal, the PLL observer effectively tracks the rotor angle of the PMSM. This estimation process is conducted in a closed-loop manner, ensuring accurate and reliable angle estimation even in the presence of system disturbances and noise.

According to Fig. 2, the angle error Δe can be estimated as shown in (10):

$$\Delta e = \hat{e}_\alpha(k) \cdot \sin(\hat{\theta}_r(k-1)) - \hat{e}_\beta(k) \cos(\hat{\theta}_r(k-1)) \quad (10)$$

Rewriting (10) and considering (2), we obtain:

$$\Delta e = \omega_r \lambda_e \sin(\hat{\theta}_r(k) - \hat{\theta}_r(k-1)) \quad (11)$$

Since the quantity $\hat{\theta}_r(k) - \hat{\theta}_r(k-1)$ tends to be small ($\sin(\hat{\theta}_r(k) - \hat{\theta}_r(k-1)) < \pi/8$), we have:

$$\Delta e = \omega_r \lambda_e (\hat{\theta}_r(k) - \hat{\theta}_r(k-1)) \quad (12)$$

From (12), a simplified diagram of the PLL is shown in Fig. 3.

Thus, the transfer function of the PLL can be written as follows:

$$\frac{\hat{\theta}_{rPLL}(s)}{\hat{\theta}_r(s)} = \frac{\omega_r \lambda_e \left(K_p + \frac{K_i}{s} \right)}{1 + \omega_r \lambda_e \left(K_p + \frac{K_i}{s} \right)} \quad (13)$$

where $\hat{\theta}_r(s)$ and $\hat{\theta}_{rPLL}(s)$ are the estimated electrical angles using the Luenberger observer and the PLL estimated angle, respectively.

$$\frac{\hat{\theta}_{rPLL}(s)}{\hat{\theta}_r(s)} = G_{LPF} \times \frac{\omega_r \lambda_e \left(K_p + \frac{K_i}{s} \right)}{1 + \omega_r \lambda_e \left(K_p + \frac{K_i}{s} \right)} \quad (17)$$

4. ENHANCED PROPOSED PLL-BASED ESTIMATOR

This study introduces an enhanced position estimation technique for PMSMs by incorporating two LPFs at the input of the PLL algorithm. This novel proposal aims to improve the estimation accuracy by reducing the impact of high-frequency noise and disturbances on the position estimation process.

The implementation of the proposed method involves using the dual LPF configuration to preprocess the input signal before it is fed into the PLL, as shown in Fig. 4.

The LPFs effectively filter out unwanted high-frequency components, resulting in a smoother back-EMF waveform [10]. This filtered input provides a cleaner and more reliable signal for the PLL, thereby enabling an enhanced estimation of the rotor position.

Applying the same principle as shown in Fig. 3, the diagram block of Fig. 4 can also be simplified, as shown in Fig. 5. The LPF transfer function can be written as shown in (14) [20]:

$$G_{LPF} = \frac{\omega_c}{s + \omega_c} \quad (14)$$

The cutoff frequency can be obtained as follows:

$$\omega_c = 2\pi f_c \quad (15)$$

where f_c is the low-pass filter's cutoff frequency.

The proposed cutoff frequency can be obtained by considering it as follows:

$$f_c \cong f_s \cdot 10^{-1} \quad (16)$$

where f_s is the system's frequency.

Thus, the transfer function of the simplified enhanced PLL can be written as follows:

5. SIMULATION AND EXPERIMENTAL VERIFICATION

To ensure accurate control of the PMSM, we use the widely adopted field-oriented control (FOC) algorithm. The FOC algorithm enables the decoupled control of the motor's torque and flux, enhancing its overall performance. The FOC algorithm incorporates the motor model, current controller, and sensor rotor angle. By precisely regulating the motor currents and controlling the flux orientation, the FOC algorithm optimizes the motor's operation and response [21].

Fig. 6 illustrates the comprehensive system block diagram in Simulink, showcasing the interconnected components of the entire system.

The diagram encompasses the PMSM model and the FOC controller block, which contains the Luenberger observer and the PLL algorithm, as shown in Fig. 7. The simulation model aims to demonstrate the effectiveness of the proposed position estimation method.

The Luenberger observer and the enhanced PLL estimator obtain the estimated position and compare it with the sensor position when the reference position of the sensor is in conjunction with the FOC controller.

The system block diagrams for the Luenberger observer and the PLL estimator are shown in Figs. 8 and 9, respectively. These diagrams highlight the integration of the observer and estimator blocks within the FOC controller algorithm in the MATLAB/Simulink environment.

Table I represents the values and parameters used in the Simulink simulations for the evaluation, such as the PMSM machine parameters, torque, system sampling time, space-vector pulse-width modulation (PWM) frequency, current and back-EMF observer gains, PLL's proportional-integral-derivative controller gain, and the cutoff frequency of the LPFs.

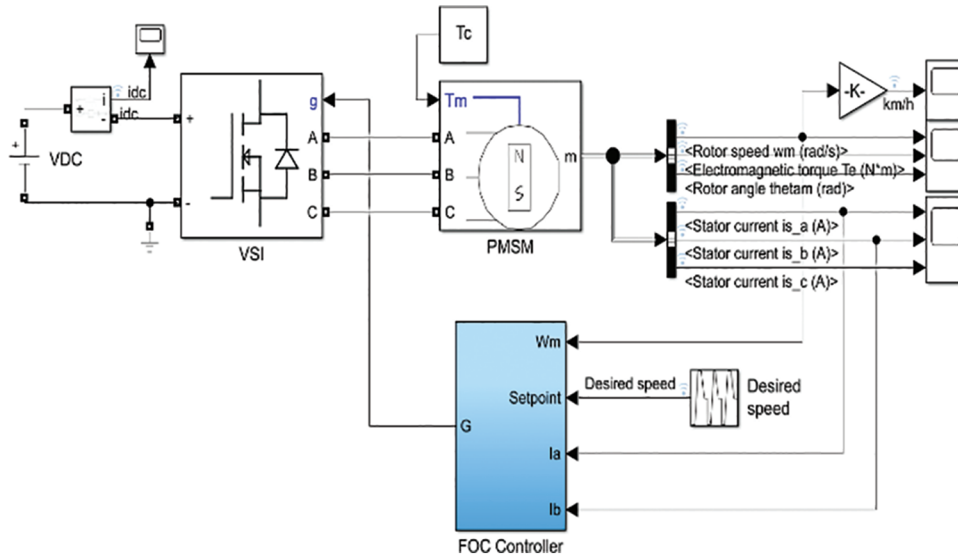


Fig. 6. System control block diagram.

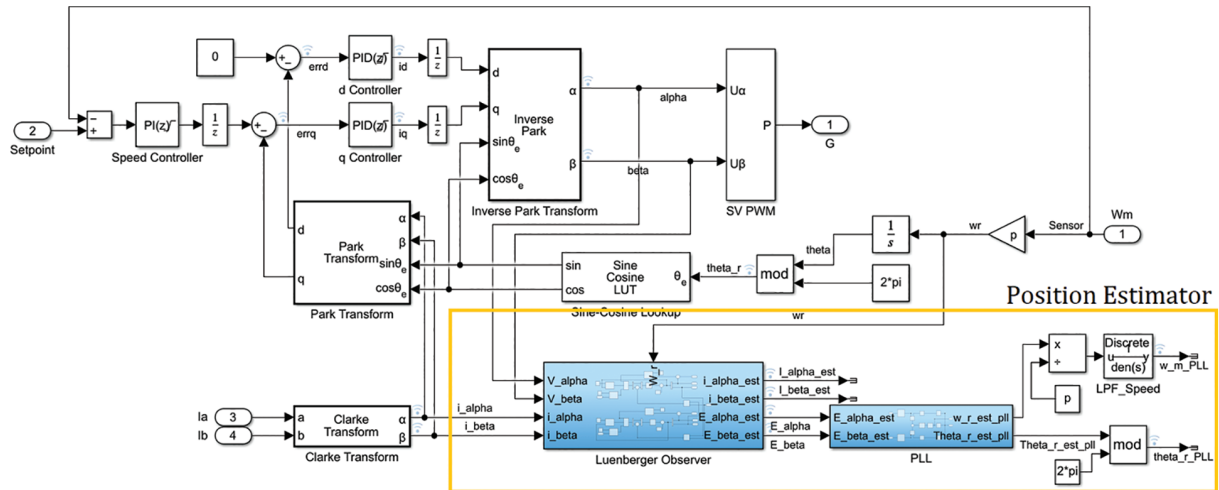


Fig. 7. FOC Controller block diagram.

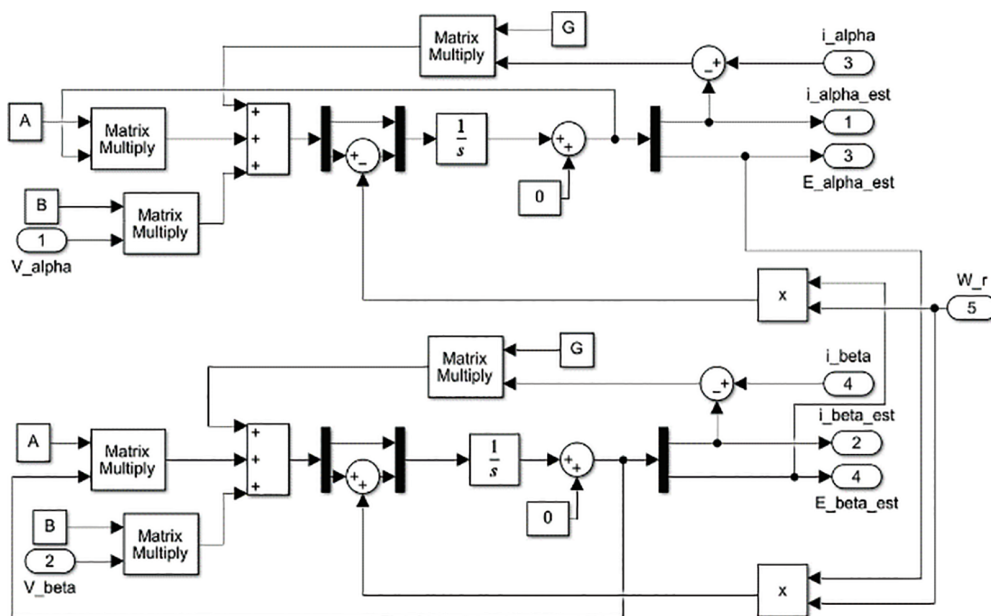


Fig. 8. Luenberger observer block diagram.

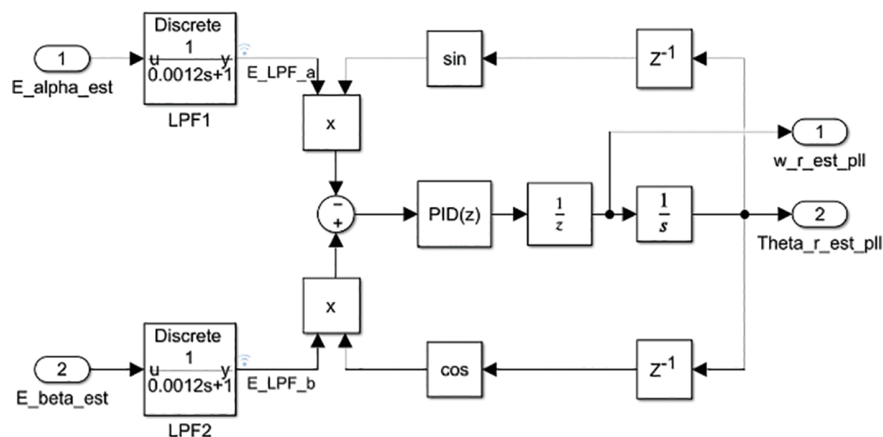


Fig. 9. PLL estimator block diagram.

These parameters were carefully selected to ensure realistic modeling of the PMSM system and accurate estimation of the motor's position.

Fig. 10 illustrates the results of the estimated back-EMF during the first 0.15 s using the Luenberger observer

compared with the filtered back-EMF obtained through the LPF of the PLL estimator's input in Fig. 11. The x-axis represents time (t), and the y-axis represents the amplitude of the back-EMF. The plot clearly demonstrates the effectiveness of our proposed method accurately estimating the

TABLE I: SYSTEM NOMINAL PARAMETERS

Parameter	Value	Unit
Stator resistance R	0.15	Ω
q-d Inductance	0.16e-3	H
Rated voltage	52	V
Machine power	1K	W
Pole pair	23	—
Electrical constant K_e	78.2	Vp/Krpm
Torque	5	N.M
SV-PWM freq	15K	Hz
System sampling time	50	s
Current observer gain g_i	8000	—
Back-EMF observer gain g_e	-21000	—
PLL K_p	105.5	—
PLL K_i	0.5	—
PLL K_d	0	—
LPF cutoff frequency	840	Hz

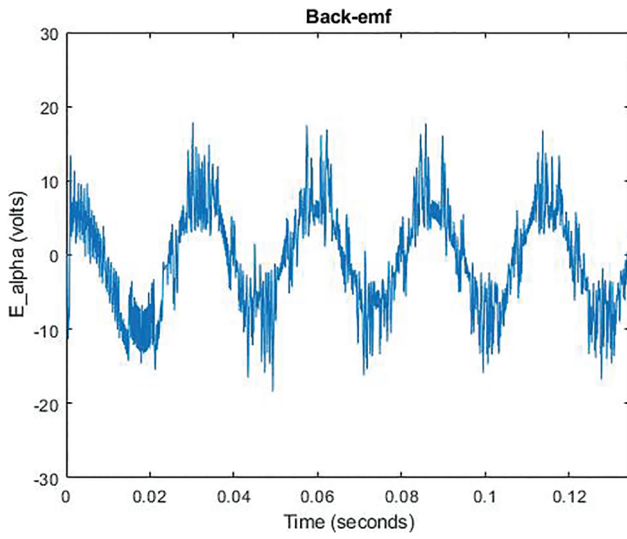


Fig. 10. Back-emf estimated.

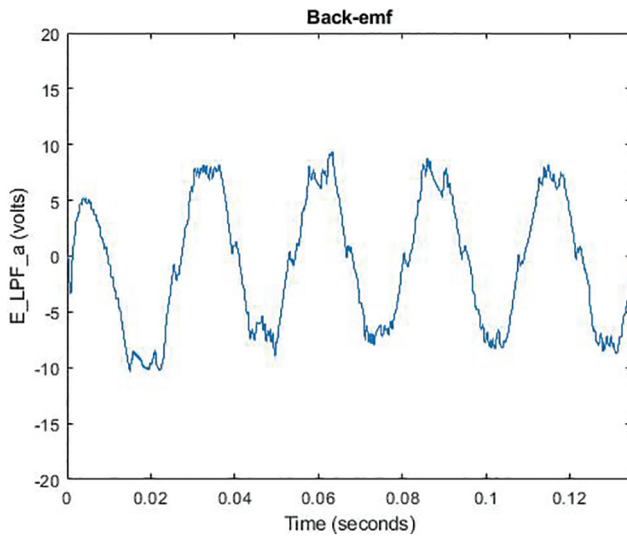


Fig. 11. Back-emf estimated and filtered through LPF.

back-EMF, as the estimated back-EMF closely matches the filtered back-EMF.

The results demonstrate the ability of our method to accurately estimate the rotor angle, providing valuable

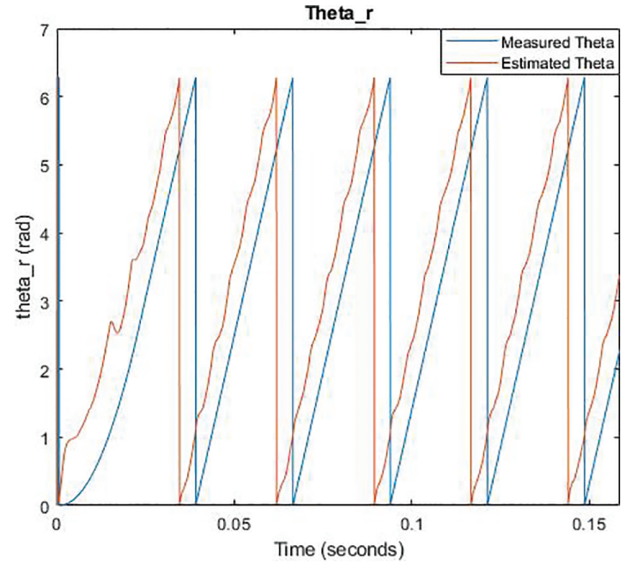


Fig. 12. PLL angle estimator versus real angle.

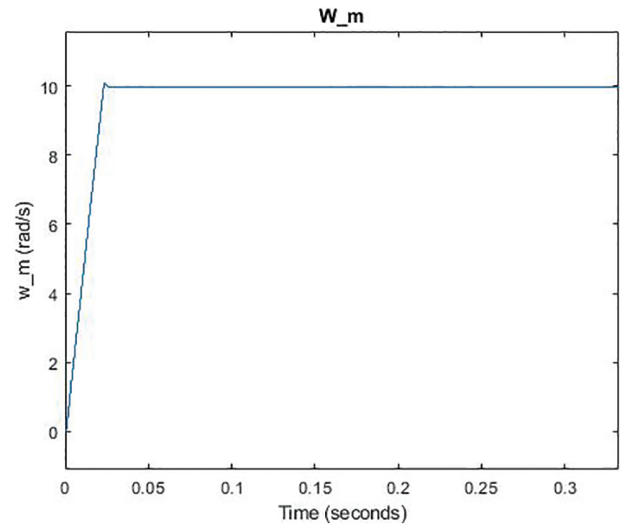


Fig. 13. Real angular speed for a set point of 10 rad/s.

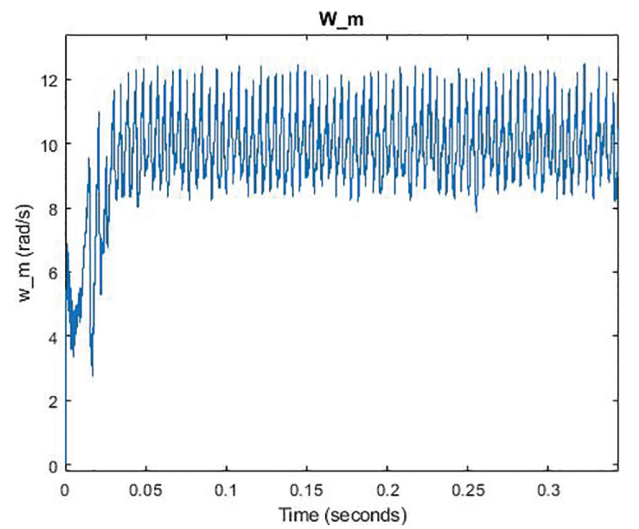


Fig. 14. Estimated angular speed from the conventional PLL estimator for a set point of 10 rad/s.

information for motor control and position tracking applications. The estimated rotor angle is in accordance with

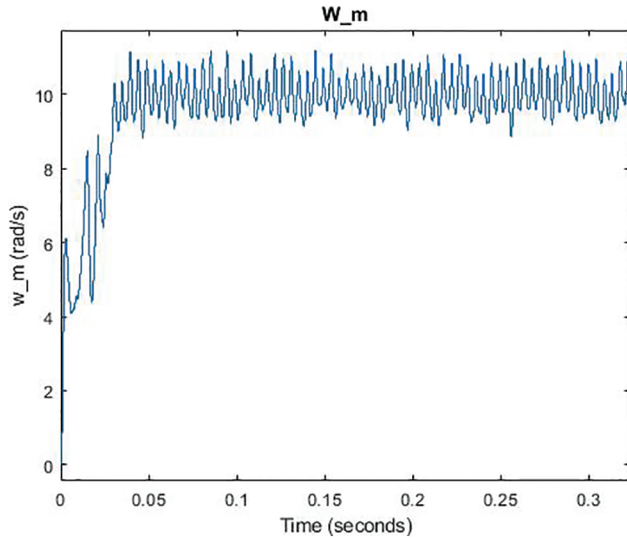


Fig. 15. Estimated angular speed from the enhanced PLL estimator for a set point of 10 rad/s.

TABLE II: SIMULATION RESULTS

Parameter	Conventional PLL	Enhanced PLL	Unit
Phase delay (average)	0.0018	0.0045	s
Position error (average)	3.2	0.9	Degree

the literature [6], [21], [22] since the estimated rotor angle is preceded by the angle measured within a small period.

Fig. 13 showcases the real angular speed in rad/s for a speed ramp of 10 rad/s. Fig. 14 shows the estimated angular speed in rad/s obtained from the conventional PLL estimator with the results from the enhanced PLL estimator, as depicted in Fig. 15.

The plot in Fig. 14 clearly highlights the superior performance of our proposed enhanced method when compared with the plot in Fig. 15, as it consistently provides more accurate estimations of the angular speed compared with the conventional PLL estimator demonstrated in [6], [22].

Table II represents a comprehensive compilation of the simulation results during the first half second of the simulation obtained from the analysis of Figs. 12–15, where it compares both the conventional PLL and the enhanced PLL responses to the real angle response.

6. CONCLUSIONS

In conclusion, the results obtained from the simulations demonstrate the effectiveness and superiority of the enhanced PLL algorithm with dual LPFs in improving the accuracy of estimating the PMSMs position.

Comparing the conventional PLL approach with the enhanced PLL, several key parameters were evaluated. The average phase delay for the conventional PLL was measured at 0.0018 s, whereas the enhanced PLL with the dual LPFs exhibited a slightly higher average phase delay of 0.0045 s. However, the increase in phase delay was outweighed by the significant reduction in position error.

The average position error for the conventional PLL was measured at 3.2 degrees, indicating a noticeable deviation from the actual rotor position. In contrast, the enhanced PLL with dual LPFs achieved a remarkable improvement, resulting in an average position error of only 0.9 degrees. This substantial reduction in position error signifies the enhanced accuracy and precision achieved by incorporating the dual LPFs into the PLL algorithm.

These results highlight the effectiveness of the proposed enhancement, showcasing the ability of the enhanced PLL to mitigate the impact of high-frequency noise and disturbances, leading to a more reliable and accurate position estimation. The reduced position error observed in the enhanced PLL is crucial for precise control and optimal performance in PMSM applications.

Overall, the enhanced PLL algorithm with dual LPFs presents a valuable contribution to the field of estimating the position of PMSMs. The results obtained validate the effectiveness of this approach in improving the accuracy and reliability of position estimation, offering potential benefits for various industrial applications where precise control and motion control are essential.

Future research may require further optimization and fine-tuning of the LPF parameters to strike an optimal balance between phase delay and position error. Additionally, experimental validation of the enhanced PLL algorithm on real-world PMSM systems proposed in this study will be valuable to confirm the results of the simulation and assess the challenges to its practical implementation.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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