MATEC Web of Conferences **404**, 02011 (2024) https://doi.org/10.1051/matecconf/202440402011
*MENEC 2024*

# A review of sensorless permanent magnet synchronous motors with adaptive observer

*Weiwen* Ding*

School of Control and Mechanical Engineering, Tianjin Urban Construction University, 300000 Tianjin, China

**Abstract.** With the widespread use of Permanent Magnet Synchronous Motor (PMSM) in industrial applications, sensorless PMSM has a major advantage over conventional PMSM. This work examines sensorless PMSM with adaptive observers, encompassing important methods such as the sliding mode observer (SMO), adaptive nonlinear extended state observer (ANLESO), Luenberger observer, and extended Kalman filter (EKF). These methods are investigated with the aim of achieving accurate observation and estimation of parameters such as rotor position in PMSM systems, and their effectiveness in solving the problems of insufficient torque and the high energy consumption is analyzed. The operational challenges of PMSM are briefly reviewed at the outset of this paper, and then the control strategies of the four previously stated methodologies are thoroughly described, with an emphasis on the benefits of these approaches in sensorless PMSM. The article concludes by summarising the research progress and future directions of these techniques, pointing out their potential to improve PMSM performance and stability.

## 1 Introduction

In today's motor control world, sensorless PMSM systems offer higher efficiency and reliability compared to traditional sensor systems. Among them, the application of adaptive observer techniques in sensorless PMSM systems has attracted much attention. This paper's goal is to present a technical analysis of this field with an emphasis on the use of adaptive observers, namely techniques like the SMO, ANLESO, Luenberger observer, and EKF.

Conventional PMSM systems usually require the installation of position sensors to obtain rotor position information, but this increases system cost and complexity. Therefore, the development of sensorless technologies is essential to simplify system architecture, improve system reliability and reduce costs. Adaptive observer technology eliminates the need for position sensors by utilising motor models and feedback information to enable accurate estimation of key parameters such as motor rotor position.

The system dynamic model and sensor feedback are combined by the EKF to enable the estimation of the PMSM system state. The Luenberger observer estimates the state variables by linearising the system's dynamic equations and is suitable for situations where the system's dynamic model is known. SMO combines sliding mode control theory and observer design

* Corresponding author:dswww@usf.edu

with robustness to parameter variations and measurement noise. Adaptive ANLESO-free, on the other hand, is an innovative approach to estimating the system state by means of adaptive learning algorithms for situations where the dynamic model of the system is unknown or difficult to model. In this paper, we will analyse the performance, stability and applicability of these adaptive observer methods in sensorless PMSM systems. By exploring in depth the advantages of these methods . It is intended to provide useful guidance for the design and control of sensorless PMSM systems. In addition, this paper will explore future research directions to promote the further development and application of adaptive observer technology in sensorless PMSM systems.

## 2 EKF optimisation and applications

Conventional PMSM drives use sensors to measure the speed of the motor, which is costly, unreliable, complex, environmentally limited and susceptible to interference. PMSM reduces costs, improves reliability and reduces system complexity through sensorless control. The EKF also has a number of advantages for sensorless PMSM control which provide accurate estimates.An implementation and optimisation method of EKF for PMSM sensorless control was proposed by Dilys, et al [1]. The EKF continuously calibrates the model to provide the best state estimate. The implementation and optimisation of the EKF aims to minimise the execution time of the algorithm while maintaining accuracy for efficient control of the PMSM system. By separating the calculation of the Kalman gain and covariance matrices, as well as the prediction and measurement state update phases, the EKF increases computing efficiency while preserving a precise approximation of the system state [1]. By minimizing the overall time consumption of the EKF method without sacrificing accuracy, this research aims to solve the optimisation challenge in sensorless control of PMSMs and, consequently, the computational efficiency problem. This methodology has the advantage of offering an optimized EKF estimation method that guarantees accuracy while minimizing the EKF algorithm's execution time. The strategy also makes use of ARM Cortex-M3 microcontrollers, which are inexpensive, low-power devices that can provide 32-bit performance in place of the current 8-bit devices. However, this approach has some drawbacks and despite proposing an optimised EKF estimation method, it still faces long execution time and hardware-software integration challenges in practical applications. Future research needs to further optimise the computation time of the EKF and delve into its applications and challenges in engineering practice.

The motor parameters of the PMSM change under operating conditions due to the effects of temperature, saturation effects and non-linearity of the voltage source inverter. Precise estimation of the motor parameters can enhance the system's control performance. Naikawadi et al. proposed a d-q axis inductance estimation of PMSM using EKF to accurately estimate motor parameters [2]. This study mainly addresses the inductance estimation problem of PMSM. The advantage of this method is that it is efficient. The EKF algorithm is able to converge to the actual values in a very short time and provide an accurate estimation of the system state. The EKF algorithm can reject process and measurement noise with similar accuracy to UKF and MHE. Meanwhile, the EKF algorithm is suitable for the estimation of PMSM parameters, which helps to improve the performance of the motor controller. Nevertheless, there are inherent difficulties in estimating the inductance of a PMSM using the EKF.The performance of the EKF algorithm is affected by the initialisation matrix, the value of which needs to be determined by trial and error methods. It is important to exercise caution when implementing EKF since longer computation times can result in empty element matrices showing up and degrading system performance. Errors exist in the system's parameter estimation because of the permanent magnet synchronous motor's magnetic saturation and temperature fluctuations in the surrounding environment. As well as the complexity and computational burden of the algorithm. These challenges highlight the shortcomings and difficulties that need to be considered when implementing EKF. Optimisation of this research can be further improved in the future in terms of joint estimation, computational time optimisation, and parameter estimation methods.

In order to resolve the issue of speed sensor-less control in PMSM drives.Nordin, et al. proposed the use of EKF for sensorless control, accurate estimation of state variables and reduction of system noise and fluctuations [3]. However, there are limitations to this method, and connecting the actual sensor signals to the controller may be impractical in some special environments, such as heavy or harsh environments and excessive wire lengths, which may affect the applicability of the sensorless control method. Adapting to the environment presents obstacles. The estimation of a nonlinear system is necessary for the EKF technique, which could make the system more complex and necessitate the use of greater processing power and algorithmic optimization. Conventional observers may have difficulty detecting phase voltages under low-speed conditions and therefore may have limitations in low-speed applications. In summary, sensorless control methods may have challenges of adaptability and algorithmic complexity in particular environments. In the future, the focus should be on improving algorithm optimisation, environmental adaptability, real-time performance, and integrated applications. Provides a more efficient and reliable control solution for PMSM drive systems.

## 3 Luenberger position observer position estimation and control strategy

The state variables of a PMSM are important for achieving accurate motor control, but not all of them can be measured directly. Specifically, in the absence of a position sensor, it is frequently necessary to estimate the rotor's position and speed using an observer. On the other hand, the Luenberger observer dynamically uses a mathematical model of the motor and the system's inputs and outputs (such as voltages and currents) to estimate internal states (such rotor angle and speed) that cannot be directly monitored. For a sensorless PMSM control system, Zhu et al. presented a Luenberger position observer based on deadband current predictive control. To lessen the effect of oscillations in PMSM parameters and the time lag between current sampling and command value update on control performance, a novel current prediction control technique is put forth [4]. This approach is based on a discrete mathematical model of PMSM, in which a deadband current prediction method is used to determine the expected current value and an integrator is used to calculate the current compensation value. The impact of parameter fluctuations and time delays on system performance is effectively addressed. The approach also adds a second-order PLL position tracker and a Luenberger observer, which enhances the PMSM system's control performance, particularly in addressing phase lag and parameter fluctuation issues. A possible disadvantage of this method is that more practical engineering verification may be required in real engineering applications to prove its effectiveness under different working conditions. Moreover, the technique may face several challenges in practical engineering applications, such as how effectively it functions in different load circumstances and how changes in system parameters impact control efficacy. Therefore, future research can further explore the robustness of the method, its feasibility in practical engineering applications,its performance under complex working conditions. In the future, this research can be optimised in the following directions. To begin with, researchers can further study how to improve the robustness of the system to parameter fluctuations to ensure the reliability and stability of the control system in practical engineering applications. Further engineering validations are conducted to ascertain the efficacy and viability of the novel current control methodology across diverse operational scenarios and to substantiate its efficacy in real-world applications.It is also possible to study the performance of the method under complex operating conditions, such as the control performance under different load conditions and the effect of changes in system parameters on the control performance. In order to address the impact of PMSM parameter variation on control performance and to enhance the system's resilience and adaptability, research is also being done on how to implement self-adaptation of system parameters. Enhancing the control system's dynamic reaction performance involves optimizing its real-time performance to guarantee that it can attain the intended value for the actual current in a single control step. Through in-depth research and optimisation in these directions, the performance of new current control methods in sensorless PMSM control systems can be further improved to promote the development and application in this field.

A Luenberger observer-based PMSM dual continuously predictive control system was proposed by Chen et al. The system makes use of the Deadband Predictive Current Control (DPCC) algorithm to design the current controller and the Model Predictive Control (MPC) algorithm to design the speed controller. A Luenberger observer is used to compensate for load disturbances, enhancing the system's robustness and immunity to interference [5]. This method has the ability to increase the system's fluid responsiveness efficiency and consistent state accuracy, together with its strong resistance to load interference. By compensating for load disturbances with a Luenberger observer, the system is able to achieve higher control accuracy and better tracking performance. The complexity of this technology restricts its potential to improve the equilibrium dependability and responsive efficacy of the system. However, the MPC algorithm and the deadband prediction current control algorithm can both be further improved in the future by enhancing the control algorithms. The observer's parameter setting is optimized to increase the system's resilience and immunity. Extending the domains in which the control approach can be used, such as factory control, battery-powered vehicles, wind power generation, etc.

Zhang et al. looked into the vector control of PMSM using a sensorless active disturbance rejection control (ADRC) technique based on a Luenberger observer [6]. Study results show that ADRC control method performs better in terms of steady state error and load disturbance resistance. This study focuses on addressing the challenges in sensorless PMSM control systems, including weak active interference, large fluctuations in steady-state velocity amplitude, and the difficulty of balancing overshooting quantities with velocity control. The advantages of this method are improved accuracy and stability of speed control, reduced amplitude of steady-state speed fluctuations, and enhanced robustness of the system to load disturbances. In addition, the use of a sensorless control method reduces cost, size, and weight, while the estimation of the PMSM position is achieved by a Luenberger observer, which improves the reliability of the system. However, implementation of the method may require fine tuning of the control parameters, in-depth mathematical modelling and analysis, as well as the handling of complex matrix operations in some cases. Overall, the approach offers significant advantages in improving the performance of PMSM control systems but may require more technical and resource investment during implementation and commissioning.

## 4 Accurate state estimation and performance optimisation of SMO in PMSM drive systems

In the field of PMSM control, SMO is an important observer design for high-precision state estimation, especially in the presence of model uncertainty and external perturbations. This observer introduces nonlinear control techniques to increase the system's resilience and immunity by utilising the sliding film control principle. A new adaptive sliding mode observer for the estimation of rotor position and velocity of PMSMs in sensorless controlled electric vehicle drive systems is presented by Xiao et al [7]. By adopting a tangential hyperbola function instead of a sign function in conjunction with a changing boundary sheet, the observer successfully decreases both the jitter problem inherent in typical sliding-based observers and the stator voltage instability induced by variations in motor temperature. In the interim, the overall robustness and flexibility are enhanced by constructing a new adaptive rule using the inverse potential model. The Lyapunov approach is used to guarantee the stability of the suggested algorithm for finding the stator resistance. The observer's implementation in an electric vehicle drive system effectively eliminates the jitter phenomena and greatly increases the estimation accuracy of rotor position and speed, as confirmed by simulation and experimental findings.

Yao et al. describe a second-order adaptive sliding mode observer control technique for position sensorless PMSMs [8]. The approach shows enhanced performance in the experiments and effectively addresses the jitter issue in the standard moving observer algorithm by applying the Lyapunov stability criterion and integrating adaptive estimating. This study provides an efficient and dependable position sensor-less management method for the PMSM control network. The drawback of this study approach is that it can only be used at medium and high speeds at this time, and at low speeds, the accuracy of the rotor speed and position prediction is insufficient. Consequently, to address the issue of estimation accuracy at low speeds, it will be necessary in subsequent research to further optimize the motor control algorithm and take into account the use of a composite control approach.

Liu et al. presented a sliding mode observer (STA-SMO) for sensorless control of integrated PMSM that is based on an over-torque technique in conjunction with adaptive parameter estimation control (APEC) [9]. The method combines STA-SMO and APEC to solve the CSMO problem and improve the observation accuracy and system robustness. This is important for solving the parameter matching problem in IPMSM sensorless control. However, the disadvantage of this approach is that the implementation process requires complex parameter adjustment and debugging of the algorithm, and more experimental validation and engineering applications may be required to further confirm its feasibility and stability. This approach has numerous applications in industrial automation and electric vehicle technology. In the future, this strategy could be improved in a number of ways, such as by expanding it to the minimal speed variety to support a wider range of rate range operations.

## 5 Performance and stability of ANLESO in sensorless PMSM control

ANLESO sensorless speed control for PMSM is presented by Gan et al [10]. By measuring the inverse electromotive force (back-EMF), it uses the nonlinear extended state observer (ESO) design principle to estimate the rotor location and speed. ANLESO offers less jitter, higher accuracy and no phase lag compared to conventional SMO. A Lyapunov equilibrium evaluation is employed to show that ANLESO is convergent, and an adaptive approach is used to find an equilibrium between steady state error and stability. This study provides a new and superior performance solution for sensorless control method of PMSM, which mainly addresses the problem of sensorless speed control of PMSM. However, the method may require more engineering practice and experience in design and commissioning to ensure its stability and reliability under different operating conditions. In addition, further research is needed to explore how to improve the performance of ANLESO under complex operating conditions and to address the challenges it may encounter in practical applications.

Gao et al. introduced a novel model-independent intelligent proportional-integral super-twisted nonlinear fractional-order sliding-mode management method based on a PMSM speed regulation system. [11]. Lyapunov's stability theorem and fractional order theory are used to demonstrate the stability of the approach, which combines the model-independent

ST-NLFOSMC strategy, the model-independent iPI control method, and LESO. The method performs better than other model-independent controllers in terms of resilience, dynamic characteristics, and static features, according to simulation and comparison data. This research focuses on addressing the challenges and difficulties in PMSM speed regulation systems, including parameter uncertainty, incompletely modelled dynamics and unknown external disturbances. This technique has the advantage of not requiring the real mathematical model; stability is demonstrated by fractional order theory and Lyapunov's stability theorem; also, it performs better in terms of resilience, dynamic qualities, and static properties. However, the disadvantages of this strategy may include the increased complexity of the method due to the increased parameters of the control method. Future work may require the selection of optimisation algorithms to refine the choice of parameters to further improve the performance of this control method. Future optimisations can be made in the following directions. Proposed control methods can be further refined to improve performance and applicability by selecting optimisation algorithms to optimise parameters, improving the MF-iPI-ST-NLFOSMC strategy to suit a wider range of applications, simplifying complexity, and combining it with other advanced control methods.

## 6 Conclusion

Overall, these observers have their own unique functions and environments. As technology advances, future research will focus on improving the robustness of these systems to better cope with uncertainties and changes in the environment. In addition, the research will also aim to reduce the dependence of these observers on accurate models so that they can maintain efficient operational performance even in the presence of insufficient model accuracy. At the same time, expanding the scope of their applications is also an important direction of research, with the goal of enabling these technologies to serve a wider range of industries and fields. To achieve this, future work will include cross-fertilisation of technologies with the development of new algorithms. This includes not only the integration of machine learning and artificial intelligence technologies, but may also involve the application of cutting-edge technologies such as quantum computing to explore entirely new solutions and approaches. Through these innovations and technological breakthroughs, more innovations and advances can be expected to be realised in the field of control theory and practical applications, thus promoting the development of the whole industry.

## References

1. J. Dilys, V. Stankevič, K. Łuksza. Implementation of extended kalman filter with optimized execution time for sensorless control of a PMSM using arm cortex-m3 microcontroller. Energies. **14**, 3491 (2021).
2. K. Naikawadi, S. M. Patil, K. Kalantri, M. R. Dhanvijay, A. V. Karanjkar. Inductance Estimation of PMSM Using Extended Kalman Filter. Int. J. Electr. Electron. Res. **11**, 138-142 (2023).
3. M. I. Nordin, J. M. Lazi, M. H. N. Talib, Z. Ibrahim. Speed sensorless control for PMSM drives using extended Kalman filter. J. Teknologi-Sci. Eng. **84**, 77-83 (2022).
4. Y. Zhu, B. Tao, M. Xiao, G. Yang, X. Zhang, K. Lu. Luenberger position observer based on deadbeat-current predictive control for sensorless PMSM. Electronics. **9**, 1325 (2020).
5. D. Chen, Z. Li, Y. Chen, H. Lei, H. Zhu, Q. Zeng. PMSM double loop predictive control based on Luenberger observer. J. Phys. Conf. Ser. (2021).

6. P. Zhang, Z. Shi, B. Yu, H. Qi. Research on a Sensorless ADRC Vector Control Method for a Permanent Magnet Synchronous Motor Based on the Luenberger Observer. Processes. **12**, 906 (2024).
7. X. Xiao, Y. Zhang, J. Wang, & H. Du. New adaptive sliding-mode observer design for sensorless control of PMSM in electric vehicle drive system. Int. J. Smart Sens. Intell. Syst. **9**, 377-396 (2016).
8. G. Yao, Y. Cheng, Z. Wang, & Y. Xiao. Study on a second-order adaptive sliding-mode observer control algorithm for the sensorless permanent magnet synchronous motor. Processes. **11**, 1636 (2023).
9. Y. Liu, J. Fang, K. Tan, B. Huang, & W. He. Sliding mode observer with adaptive parameter estimation for sensorless control of IPMSM. Energies. **13**, 5991 (2020).
10. M. Gan, & C. Wang. An adaptive nonlinear extended state observer for the sensorless speed control of a PMSM. Math. Probl. Eng. 1-15 (2015).
11. P. Gao, X. Lv, H. Ouyang, L. Mei, & G. Zhang. A Novel Model-Free Intelligent Proportional-Integral Supertwisting Nonlinear Fractional-Order Sliding Mode Control of PMSM Speed Regulation System. Complexity. 1-15 (2020).