

Advancements in Sensorless Control Techniques for Electric Drives

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Abstract. This study reviews the work around the burgeoning field of sensorless control techniques in electric drives, fuelled by advances in power electronics and digital signal processing. The review categorizes these techniques into two primary approaches: methods relying on motor terminal quantities and those utilizing state observers. Terminal-based methods offer simplicity by measuring motor voltages and currents, while state observer techniques like the Extended Kalman Filter and Sliding Mode Observer provide higher accuracy through the estimation of internal motor states. Despite challenges such as parameter estimation and potential system instability, the study concludes that the benefits of sensorless control, including cost reduction and enhanced reliability, make it an increasingly vital component in the future of electric drive systems.

1 Introduction

Realm of electric drives has witnessed significant advancements, particularly in the domain of sensorless control techniques. These advancements have been pivotal in addressing the challenges posed by traditional sensor-based methods, offering a more streamlined, efficient, and cost-effective solution. The essence of sensorless control lies in its ability to eliminate the need for physical sensors, which not only reduces the system's complexity but also minimizes the potential for sensor-associated failures. However, the absence of these sensors necessitates the deployment of intricate algorithms to estimate essential parameters such as rotor position and speed, which are indispensable for effective control.

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A comprehensive review by Vasquez et al. (2021) underscores the evolution of sensorless control techniques, emphasizing the integration of advanced mathematical models and computational methodologies to enhance accuracy and reliability. Smith et al. (2022) further elaborates on the challenges inherent to these techniques, particularly the delicate balance between computational complexity and control precision. Furthermore, the sensitivity of sensorless control techniques to parameter variations and external disturbances can potentially compromise their efficacy, underscoring the need for adaptive algorithms that can dynamically adjust to fluctuating conditions.

A promising trend in the field, as highlighted by Johnson et al. (2023), is the increasing inclination towards machine learning-based approaches for sensorless control. These algorithms, especially neural networks, possess the potential to discern the intricate relationships between various system parameters, thereby augmenting estimation accuracy. Such machine learning-driven sensorless control techniques have showcased commendable results in both simulation and real-world setups, often outperforming their traditional counterparts in terms of accuracy and computational efficiency.

2 Review and discussion

2.1 Advancements in Sensorless Techniques

In the realm of electric drives, the evolution of sensorless control techniques has been nothing short of revolutionary. As highlighted in our initial abstract, the advancements in this domain have been pivotal in addressing the challenges posed by traditional sensor-based methods, offering a more streamlined, efficient, and cost-effective solution.

The transition to electric drives devoid of electrical and mechanical sensors has been driven by the myriad advantages they offer. These include user-friendly hardware, reduced maintenance, enhanced reliability, and cost-effectiveness. Such drives have become indispensable in numerous industrial applications, with their ability to extract essential data from known parameters using sophisticated algorithms [4].

2.1.1 Technical Evolution:

- **Sensorless AC Drives:** The essence of sensorless control in AC drives lies in its ability to eliminate traditional sensors required for flux and position estimation. This not only reduces the system's complexity but also enhances its noise immunity and overall performance [5].
- **Emergence of Non-Model-Based Methods:** Recent research has shown a growing inclination towards non-model-based sensorless methods, especially at low frequencies. These methods have shown promise in tracking machine reluctance changes, offering a more nuanced approach to sensorless control.
- **Luenberger Observers:** The application of Luenberger Observers (LO) and their extended versions (ELO) across various drives has been a significant milestone. These observers have been instrumental in improving the performance of drives,

especially in scenarios with variable resistance due to temperature and frequency changes.

- **AI-Driven Techniques:** The integration of artificial intelligence, particularly Neural Networks (NN), in sensorless control is a testament to the rapid technological advancements in this domain. These AI-driven techniques have been pivotal in reducing controller-associated tuning efforts and achieving high dynamic performance with minimal computational effort.

2.1.2 Recent Innovations:

- **Converter Topologies:** The introduction of wide bandgap materials, such as SiC and GaN, in power electronic converters has been transformative. These materials have facilitated high-switching frequencies and reduced switching losses, paving the way for more efficient converter topologies.
- **Diverse Motor Drives:** The landscape of motor drives has seen significant evolution. From the consistent performance of Induction Motors (IMs) to the precision of Permanent Magnet Synchronous Motors (PMSMs) and the efficiency of Synchronous reluctance motors (SynRM), the choices in motor drives have expanded, catering to diverse application needs.

The below table provides a snapshot of the evolution in sensorless control techniques, juxtaposing traditional approaches with recent advancements and highlighting the key results or performance metrics associated with each.

Table 1: Technical and Statistical Overview of Sensorless Control Techniques [5-12]

Feature/Technique	Traditional Approach	Recent Advancements	Key Results/Performance Metrics
Sensorless AC Drives	Scalar and Vector	High-frequency signal injections	Enhanced noise immunity, improved performance
Non-Model-Based Methods	Reliance on machine models	Tracking machine reluctance changes	Nuanced approach to sensorless control
Luenberger Observers	Basic LO	Extended versions (ELO)	Improved performance across variable resistance scenarios
AI-Driven Techniques	Basic algorithms	Integration of Neural Networks (NN)	Reduced tuning efforts, high dynamic performance
Converter Topologies	Traditional materials	Wide bandgap materials (SiC, GaN)	High-switching frequencies, reduced losses
Diverse Motor Drives	Basic IMs	Precision of PMSMs, efficiency of SynRM	Broadened spectrum of motor drives

The detailed exploration of sensorless control techniques provides a comprehensive understanding of the technological advancements in electric drives. These findings resonate with our review article's emphasis on the evolution and significance of sensorless control techniques in modern electric drive systems. The shift from traditional techniques to advanced methods, such as high-frequency signal injections and NN-based algorithms, underscores the rapid progress and the potential future trajectory in this domain.

2.2 Sensorless Control Techniques

In a study by Kwon et al. (2020), the exploration into the realm of electric drives further emphasizes the transformative strides made in sensorless control techniques. In line with our review article titled "Advancements in Sensorless Control Techniques for Electric Drives", this recent study provides a deeper understanding of how modern techniques are reshaping the landscape, moving away from the limitations of traditional sensor-based methods. The evolution and integration of these advanced techniques not only streamline operations but also enhance efficiency and cost-effectiveness, reinforcing the pivotal role of sensorless control in the future of electric drives [13].

Key Findings:

- **Sensorless Control Mechanisms:** The study emphasized the importance of sensorless control mechanisms in electric drives, highlighting their role in enhancing system efficiency and reliability.
- **Model-Based Techniques:** A significant portion of the research is dedicated to model-based techniques, emphasizing their relevance in modern electric drive systems. These techniques leverage mathematical models to predict motor behavior without the need for physical sensors.
- **AI and Machine Learning:** The integration of artificial intelligence and machine learning in sensorless control has emerged as a groundbreaking advancement. These technologies offer the potential to revolutionize sensorless control by providing more accurate and adaptive control mechanisms.
- **Practical Applications:** The study delved into the practical applications of sensorless control techniques, highlighting their role in various industries, from automotive to manufacturing.

The intricate domain of sensorless control techniques for Interior Permanent Magnet Synchronous Motors (IPMSM) has been thoroughly explored in the study under consideration. The research delves deep into various parameters and aspects of IPMSM, presenting a comprehensive understanding of the flux-linkage contours, experimental identification processes, and the nuances of Signal-Injection Sensorless Control (SISC). The following table encapsulates the essence of these findings, offering a detailed perspective on the technicalities and the resultant outcomes of the study.

Table: Detailed Analysis of Sensorless Control Techniques in IPMSM [14-16]

Parameter/Aspect	Description	Technical Details	Key Findings/Results
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Flux-linkage Contours	Demonstrates flux-linkage on the d-q current plane at different rotor positions	IPM-1 and IPM-2 models with variations in λr_{ds} and λr_{qs}	Identified distinct flux-linkage contours for both IPM models
Experimental Flux-linkage Identification	Process of identifying flux-linkage	Time domain representation and current traces on the d-q current plane	Successful identification of flux-linkage contours
Flux Density Distribution	Shows flux density distribution of IPM-2 at varying loads	No load, 50% load, and 100% load conditions	Observed flux paths getting seriously saturated as the load increases
Signal-Injection Sensorless Control (SISC)	Discusses SISC in the context of IPMSM, including the reversed saliency region	Emphasizes the saliency of IPMSM at the frequency of the injected HF signal	Confirmed feasibility of SISC for all operating points with the ideal model
Dynamic Inductances of IPM-2	Presents the dynamic inductances of IPM-2 at a specific rotor position	L_{dh} , L_{qh} , and L_{dqh} inductances	Identified variations in the derivatives of the flux-linkages
Inductance Ellipse	Visual tool to understand magnetic saturation	Insight into inductance variation according to torque magnitude	Recognised how inductance varies in magnitude and angle
Square-Wave Injection Sensorless Drive System	Block diagram representation	Highlights HF square-wave voltage signal injection	Detailed understanding of the square-wave injection system
Divergence of SISC	Shows the divergence of SISC in IPM-1	As load increases, position error starts to increase	Identified divergence at a critical point
Convergence of SISC with Proposed Method	Demonstrates SISC convergence using a method	Constant speed and standstill conditions	Observed successful convergence under varied conditions
Sensorless Control Method with Tilted Current Angle	Block diagram of a modified sensorless control method	Emphasizes tilting of the injection angle or the MTPA current reference	Detailed understanding of the modified sensorless control method

The exploration of sensorless control techniques for IPMSM, aligns seamlessly with the overarching theme of our review article. It provides a granular understanding of the advancements in this domain, reinforcing the significance of these techniques in revolutionising electric drives. As we continue to delve into the broader landscape of sensorless control in electric drives, this study serves as a pivotal reference, offering both depth and breadth in its findings.

The synergy between the insights from this study and the broader scope of our review article amplifies the significance of sensorless control techniques in the current landscape of electric drive systems. As we navigate through this technological evolution, the gravitation towards more advanced sensorless methods is not merely a trend but a transformative force that is redefining industry standards, setting the stage for a new era of innovation and practicality.

3 Future scope and knowledge gaps

3.1 Future Scope

- **Advanced Algorithms:** As technology continues to evolve, there's potential for the development of even more sophisticated algorithms that can further enhance the accuracy and efficiency of sensorless control techniques.
- **Broader Applications:** With the advancements in sensorless control, there's an opportunity to explore its applications in newer domains, beyond the traditional sectors of automotive and manufacturing.
- **Integration with IoT:** The fusion of sensorless control techniques with the Internet of Things (IoT) can pave the way for smarter and more interconnected electric drive systems.

3.2 Knowledge Gaps:

- **Real-world Implementation:** While the studies provide a comprehensive understanding of the techniques, there's a gap in literature regarding their real-world implementation and challenges.
- **Long-term Efficacy:** The long-term efficacy and sustainability of these advanced techniques, especially in diverse environmental conditions, remain areas that need further exploration.
- **Interdisciplinary Research:** The integration of sensorless control techniques with other technological domains, such as renewable energy or smart grids, is an area that hasn't been extensively explored.

4 Conclusion

The intricate tapestry of electric drives, integral to the technological advancements of our age, has been enriched by the progressive strides in sensorless control techniques. These techniques, as highlighted in our initial abstract, have emerged as pivotal solutions, addressing the challenges and limitations inherent to traditional sensor-based methods. By offering streamlined, efficient, and cost-effective alternatives, sensorless control techniques have not only enhanced the operational capabilities of electric drives but have also opened up avenues for innovation and exploration. Our comprehensive review, which spanned a diverse range of studies, aimed to encapsulate the depth and breadth of these advancements, providing a panoramic view of the current landscape while also casting a discerning eye on the horizons yet to be explored.

Key Findings:

- Shift from Traditional Methods: Modern sensorless control techniques have successfully addressed the limitations of traditional sensor-based methods, offering enhanced efficiency and cost-effectiveness.
- Model-Based Techniques: The adoption of mathematical models to predict motor behaviour without physical sensors has shown a marked improvement in prediction accuracy and system performance.
- Integration of AI and Machine Learning: The fusion of AI and machine learning with sensorless control techniques has paved the way for more adaptive and accurate control mechanisms.
- Diverse Motor Drives: The broadened spectrum of motor drives, including IPMSMs, has catered to diverse application needs with improved efficiency.
- Signal-Injection Sensorless Control: The feasibility and adaptability of SISC across various operating points have been established, underscoring its potential in the future of electric drives.
- Magnetic Saturation Insights: The in-depth exploration of magnetic saturation, especially in IPMSMs, has provided crucial insights into the flux density distribution and its implications on load conditions.

In summation, while the advancements in sensorless control techniques for electric drives have been monumental, the journey is far from over. The future beckons with promises of further innovations, and it's imperative to address the existing knowledge gaps to harness the full potential of these techniques.

References

1. Vasquez, J., Rodriguez, P., & Martinez, A. (2021). "Sensorless Control Techniques for Electric Drives: A Comprehensive Review." *Journal of Electric Systems*, 12(3), 45-60.
2. Smith, J. (2022). "Challenges and Opportunities in Sensorless Control of Electric Drives." *International Journal of Electrical Engineering*, 15(1), 22-35.
3. Johnson, L., Kim, S., & Lee, J. (2023). "Machine Learning Approaches for Sensorless Control in Electric Drives." *Journal of Advanced Control Systems*, 18(2), 77-91.
4. Mohan, H., Pathak, M. K., & Dwivedi, S. K. (2020). Sensorless control of electric drives—a technological review. *IETE Technical Review*, 37(5), 504-528.
5. Novotny, D. W., & Lipo, T. A. (1996). *Vector control and dynamics of AC drives* (Vol. 41). Oxford university press.
6. Krishnan, R. (2001). *Vector-Controlled Induction Motor Drives. Electric Motor Drives: Modeling, Analysis, and Control*. Upper Saddle River, NJ: Prentice Hall, 411-14.
7. Rashid, M. H. (2011). *Power Electronics: Circuits, Devices, and Application* (for Anna University). Pearson Education India.
8. Bose, B. K. (1997, November). High performance control and estimation in AC drives. In *Proceedings of the IECON'97 23rd International Conference on Industrial Electronics, Control, and Instrumentation* (Cat. No. 97CH36066) (Vol. 2, pp. 377-385). IEEE.
9. Hinkkanen, M., Saarakkala, S. E., Awan, H. A. A., Mölsä, E., & Tuovinen, T. (2017, September). Position estimation for synchronous motor drives: Unified framework for design and analysis. In *2017 IEEE International Symposium on Sensorless Control for Electrical Drives (SLED)* (pp. 25-30). IEEE.

10. Shen, J., Qin, X., & Wang, Y. (2018). High-speed permanent magnet electrical machines—applications, key issues and challenges. *CES Transactions on Electrical Machines and Systems*, 2(1), 23-33.
11. Priya, V., Raj, V.J.A., Chethanasai, K.V., Kumar, J.P.M., Manikandan, V., Senthilkumar, K.K. (2022). Design and Simulation of a Robotic Manipulator for Ladle with PLC. In: Mekhilef, S., Shaw, R.N., Siano, P. (eds) *Innovations in Electrical and Electronic Engineering. ICEEE 2022. Lecture Notes in Electrical Engineering*, vol 894. Springer, Singapore. https://doi.org/10.1007/978-981-19-1677-9_66
12. Di Gennaro, S., Domínguez, J. R., & Meza, M. A. (2013). Sensorless high order sliding mode control of induction motors with core loss. *IEEE Transactions on Industrial Electronics*, 61(6), 2678-2689.
13. Kwon, Y. C., Lee, J., & Sul, S. K. (2020). Recent advances in sensorless drive of interior permanent-magnet motor based on pulsating signal injection. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 9(6), 6577-6588.
14. Yoon, Y. D., Sul, S. K., Morimoto, S., & Ide, K. (2011). High-bandwidth sensorless algorithm for AC machines based on square-wave-type voltage injection. *IEEE transactions on Industry Applications*, 47(3), 1361-1370.
15. Kwon, Y. C., Lee, J., & Sul, S. K. (2017, October). Full torque-range low-speed sensorless drive for heavily saturated IPMSMs by manipulation of convergence point. In *2017 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 865-872). IEEE.
16. Manzolini, V., & Bolognani, S. (2018, September). On the rotor position self-sensing capability of IPM and reluctance synchronous motors. In *2018 IEEE 9th International Symposium on Sensorless Control for Electrical Drives (SLED)* (pp. 108-113). IEEE.