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Rotor Position Estimation Approach for Sensor less Control of PMSM in Electric Vehicles

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***Abstract*— Electric vehicles (EVs) are promoting sustainable transportation as a reduction in fossil fuel reliance. Permanent Magnet Synchronous Motor (PMSM) is an integral part of any EV's propulsion mechanism as it offers excellent efficiency, high power density, and torque competency. Sensor-based control schemes for traditional PMSMs increase cost and reduce system lifetime when employed in harsh environments. The limitations cited above are reversed using SMO and MRAS for position estimation in rotor for sensorless control. Although SMO is robust and efficient with the chattering problem affecting smoothness, MRAS provides higher accuracy and adaptability especially at steady states at the cost of increased computational power. This paper compares the SMO and MRAS methods for controlling PMSMs in EV applications.**

***Index Terms*— Electric Vehicles, PMSM, Sensorless Control, Sliding Mode Observer, Model Reference Adaptive System, Hybrid Approach, Estimation Accuracy.**

I. INTRODUCTION

Electric vehicles have transformed modern transportation and presented a cleaner, more environmentally-friendly alternative to fossil-fueled ones. As concerns for the environment and demands for renewably available sources of energy continue to rise, EVs are very handy as a much-needed alternative because they offer greenhouse gas emissions cut and minimal reliance on fossil fuel [1]. PMSM is one of the major parts in the propulsion system of EVs because it has high efficiency, high power density, and capabilities to tolerate fluctuations during different operational conditions [2]. The PMSM's advantages make it ideal for EV applications where efficiency and reliable power delivery are indispensable for maximizing range and enhancing the driving experience [3]. PMSMs have a permanent magnet embedded in the rotor so that the magnetic field is self-sustaining, eliminating the need for any external excitation. This design reduces the losses that are attributed to the rotor currents while allowing for better utilisation of energy from the battery of the vehicle, the most significant reason which ultimately brings about a better driving range [4]. PMSMs help in making smooth acceleration and overall drivability of the EV by providing smooth torque at various speeds; this, in turn, makes it indispensable in high-performance applications for automobiles [5].

A. Precise PMSM Control Requirement

In order to achieve the best possible performance for an EV, precise PMSM torque and speed control are required. With regards to these control processes, sound foundation is found in the accurate estimation of rotor position since this is the wellspring of all operating quantities in the motor. Normally, traditional PMSM controllers use encoder and resolver-type mechanical sensors for real-time measurements of rotor position and speed. However, these sensors come with significant disadvantages: it increases the overall cost and adds weight and volume to the motor. In addition to that, it is sensitive to environmental conditions such as temperature changes, humidity, and vibrations. These factors may degrade the sensor performance and can cause failure in measurements or control [8].

Sensor-based systems also present challenges in logistics. The routine maintenance required boosts operational costs and complexity, and the installation of sensors provides potential points of failure that would compromise the reliability of the system when operated in harsh conditions [9]. With this background, the research community pursued the development of sensorless control technologies to circumvent the above limitations and to further enhance the reliability and efficiency of PMSM control for EV applications.

B. Sensorless Control Technology for PMSMs

Sensorless control has become one of the most important trends in PMSM technology, avoiding the weaknesses inherent to the sensor-based systems. With the elimination of mechanical sensors, sensorless control reduces the system's complexity and cost through improved durability under adverse conditions and improves system robustness. Sensorless control calculates rotor position and speed from the analysis of electrical signals-voltage and current-instead of involving physical sensors [10]. This gives an uninterrupted monitoring of the motor performance without much interference usages, especially suitable for the operational conditions of EVs in varying environmental

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conditions.

Among these ways of sensorless control, two methods have drawn focus in the case of PMSMs for EV applications: SMO and MRAS [11]. While each has its strengths and peculiar challenges associated with their usage, it is important to come to understand their intrinsic merits and demerits within the various modes of operation of EVs.

C. Sliding Mode Observer (SMO)

The sliding mode observer, SMO, is one of the well-known nonlinear observer techniques highly recognized for its robustness and dynamic response capabilities. It uses principles of sliding mode control based on a discontinuous control law accompanied by high-frequency switching to track rotor position and speed [12]. Its application provides very high resilience towards parameter variations, hence it should be used in cases in which motor parameters will change rapidly due to changing operating conditions. For instance, SMO can provide robustness to load and temperature variations-a typical case in many EVs [13].

The approach suffers from the so-called problem of "chattering," a form of oscillation generated by the process of high-frequency switching in sliding mode control. This chattering effect may cause inefficiencies and may even deteriorate the smoothness of the motor operation, which is considered highly significant for applications of EVs that focus on an improvement of driving experience and noise reduction [14]. Various techniques, such as low-pass filters have been proposed for reducing the chattering; however, the approach adversely affects system responses and overall performance [15].

D. Model Reference Adaptive System (MRAS)

Another well-known approach to sensorless PMSM control is the Model Reference Adaptive System (MRAS), with results particularly appreciated for their accuracy and adaptability. MRAS operates based on principles that compare the outputs of a reference model which would ideally describe motor operation and a structured and adaptive model that incorporates the estimated parameters. Adjusting those parameters in such a way as to minimize the error between the two models results in the rotor position and speed estimates being very accurate [16].

MRAS is highly efficient under steady-state conditions, where it possesses a smoother operation compared to SMO and could be considered for high-performance applications with EVs requiring high accuracy in state estimation. However, MRAS has its drawbacks as well. This method generally demands more computation resources than SMO due to the adaptive modeling algorithm used. Furthermore, although MRAS systems may be faster for certain types of adaptation, the response time under dynamic conditions may be slower due to the delay in model adaptation processes tracking rapid changes of the motor parameters [17].

Another drawback of MRAS is the requirement that there needs to be a well-defined reference model. The reference model must be finely calibrated to approximate the real motor dynamics, and any mismatch in the models creates possibilities for estimation errors. The development of high-fidelity reference models may be highly complicated and resource-intensive, which could restrain the applicability of MRAS in environments with fast-changing dynamics or very high levels of noise, in which maintaining model fidelity becomes challenging [18].

E. Compare SMO and MRAS for EV Applications

The two controls, namely SMO and MRAS, can be counted as good alternatives for sensorless control of PMSM-based EVs based on merits associated. SMO control is preferred for applications that highlight the need for robustness, efficiency, and lower computational requirements; hence, the usage of such a system in EVs that are exposed to variable unpredictable conditions varying with time. By contrast, MRAS is advantageous when a higher precision and smoothened operations are in demand, especially for constant velocities, with an important consideration in premium EV models that claim a high comfort for the drivers as well as good accuracy in their performance [19].

Comparing the trade-offs between SMO and MRAS, it reveals the possibility of combining both systems and creating a hybrid system that could leverage the complementary strengths of these two methods. The hybrid combination of the resilience of SMO with the precision of MRAS is likely to generate a sensorless control system capable of dynamical adaptation to simultaneous variations in high speeds as well as steady-state conditions, optimizing its performance over a wider range of EV operating scenarios [20]. This hybrid combination would overcome the challenges presented by both methods and could offer a possible solution where accuracy, efficiency, and adaptability are balanced for next-generation applications in EVs.

F. Contributions of This Paper

This paper represents a comparative analysis of SMO and MRAS techniques for sensorless PMSM control of EV. The comparison of these approaches under different conditions on the basis of simulation is done by the study, and some of the respective trade-offs related to the accuracy of estimation and computational complexity, along with their impact on EV efficiency, are highlighted. The outcome of the work aims to inform on the choice of effective control strategies for various topologies of EV and associated operational requirements, as well as the capability of a hybrid SMO-MRAS strategy as a potential future research path for PMSM control in electric vehicles.

II. LITERATURE REVIEW

Yadav et al., (2020) studied a rotor position estimation scheme specifically designed for PMSM drives, focusing on

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the advantages of sensorless control to decrease system cost and complexity. An algorithm based on adaptive techniques for the estimation of the rotor position was proposed and implemented in an EV powertrain simulation. Possible improvements in the position accuracy and steady-state performance have been noticed under various load conditions and the potential has been highlighted for use in EVs [1].

Ferdiansyah and Hanamoto, 2024 proposed an innovative sensorless control method that encompasses high-frequency voltage injection through an FPGA-based way, which was integrated with a novel extraction method of rotor position estimation. The approach, therefore increases the accuracy of rotor position detection since it raises the flexibility level in control and decreases the computational load as well. As revealed by the outcome of the research, the approach had high accuracy in conducting its experiment on the estimation of rotor position, thereby making it suitable for PMSM control in EV applications, primarily at low speed and dynamic acceleration [2].

Kuruppu and Abeyratne, (2022) looked into the fault detection techniques for applications of PMSM applications, thereby distinguishing uniform demagnetization faults from position sensor faults. Their approach relied on fault tolerant control algorithms such that distinctive fault signatures can be identified, improving the reliability of field-oriented control FOC systems for PMSMs. They concluded that their proposed method would definitely differentiate the type of faults to enable more precise diagnostics and fewer chances for the misinterpretation of PMSM control [3].

Li et al., (2021) conducted an in-depth review of the techniques for rotor position estimation for sensorless control in EV applications. They have learned some approaches, including SMO and MRAS, that have high emphasis on their real-time effectiveness and limitations. Robustness of SMO and adaptability of MRAS are identified as strengths; however, challenges were seen in the chattering in SMO and increased computational complexity in MRAS, and thus, future research should be based on combining both methods to enhance the accuracy of control [4].

Based on an adaptive phase-locked loop PLL-based control scheme, which was designed to improve the dynamic response of a high-speed PMSMs, Novak and Novak, 2022 proposed their method. Utilizing the adaptive mechanisms of PLL, they had estimated rotor position without physical sensors with much smoother performance in sensorless control systems. They claim great performance in terms of dynamic response improvement and concluded that the adaptive PLL-based control would be a promising alternative for high-speed applications of EVs [6].

Sun et al., (2022), looked into finite position control for interior PMSMs at low speeds, developing an algorithm which optimally controls the parameters for stable performance. The control strategy reviewed was suitable for low speed application where sensorless estimation is difficult. Their results were proved to be valid both by accuracy and stability when working under low speed thus making the approach viable even for precision EV applications [7].

Sun et al., (2023) studied the adaptive energy control management strategy ECMS enhanced by grey wolf optimization and neural networks for plug-in hybrid electric buses. This enhanced control strategy therefore optimized gear shifting and minimized energy consumption. Their method demonstrated enhanced energy efficiency and the feature of adaptive control in support of efficient PMSM management within the confines of hybrid EVs and points to even broader uses in EVs. [8]

Sun et al., (2022) introduced a hybrid control strategy that combined time scale factor TSF and linear active disturbance rejection control LADRC to enhance the performance of speed control SRMs using a modified grey wolf optimization algorithm. This hybrid approach allows for more adaptive control over different conditions, achieving stable and efficient performance over a wide range of both speeds and loads that may benefit for EV motor control systems [9].

In this research, Sun et al., (2022) analyzed adaptive energy control management for hybrid electric buses using model predictive control with efficiency-focused EF optimization. In this study, an adaptive ECMS was used to optimize fuel consumption as well as the energy distribution. Significant improvements in efficiency were shown, and the presented method, one which was adaptive, proved to be very effective in complex EV powertrains that require fine-tuned energy management [10].

Woldegiorgis et al., (2022) developed an active flux estimation strategy for sensorless control of interior PMSMs. The proposed method estimated flux in a reference frame, which improved the accuracy in the estimation of the rotor position. This technique ensured precise and responsive control at a wide operational range without much reliance on physical sensors. Their work thus proved that active flux estimation yielded higher performance in the sensorless PMSM control for demanding applications in EV [11].

Xu et al., (2023) reviewed position-sensorless technology for PMSM systems, targeting the performance of different sensorless control techniques under conditions of SMO and MRAS. They showed that SMO works better at cases with demands of higher robustness, although high accuracy in steady-state condition can be ensured with the use of the MRAS technique. A research review of both techniques in a hybrid framework highlighted that this type of use could be critical to achieving more adequate sensorless control in EVs, particularly on control precision and flexibility [12].

III. PROPOSED SYSTEM

The proposed system compares the relative improvement of two advanced control techniques concerning sensorless control for Permanent Magnet Synchronous Motors applied in electric vehicles with Sliding Mode Observer and Model

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Reference Adaptive System. It reduces the reliance on physical sensors, hence lowering the cost of construction and making the system more robust for use in harsh environments. SMO is powerful and fast in response. It accomplishes the estimation of rotor position by switching with high frequency but, at the same time, is always a victim of chattering. Mras is very accurate and smooth due to comparisons of two models, the reference model and the adaptive model, but the computational resources are more for it and has slow response with dynamic conditions. This system will evaluate the comparative merits based on the accuracy of rotor position estimation, efficiency, and impact on the performance of the EV through simulations. The project thus culminates in suggesting a hybrid SMO-MRAS approach that draws the merits of the resilience of SMO together with the precision of MRAS to present a flexible accurate, and robust control solution adaptable to all kinds of operating scenarios in EVs.

IV. MATHEMATICAL APPROACH

A. PMSM Modeling in d-q Frame

The PMSM dynamics are represented in a two-phase rotating (d-q) reference frame. The governing voltage equations are derived as follows:

$u_{sd} = R_s i_{sd} + (d\Phi_{sd}/dt) - \omega\Phi_{sq}$

$u_{sq} = R_s i_{sq} + (d\Phi_{sq}/dt) + \omega\Phi_{sd}$

where u_{sd} and u_{sq} are the stator voltages in the d and q axes, R_s is the stator resistance, i_{sd} and i_{sq} are the stator currents, Φ_{sd} and Φ_{sq} are the stator flux linkages, and ω is the electrical angular speed of the rotor.

The electromagnetic torque, T_e, generated by the motor is expressed as:

$T_e = 3/2 P \lambda_m i_{sq}$

where P is the number of pole pairs, λ_m is the permanent magnet flux linkage, and i_{sq} is the q-axis current. These equations set the basis for implementing both SMO and MRAS techniques to estimate rotor position and speed.

B. Sliding Mode Observer (SMO)

The SMO approach involves switching control laws to estimate rotor position and speed. The SMO dynamics in the α−β frame (stationary reference frame) are given by:

$$p\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = -\frac{R_s}{L_s}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} e_\alpha - k_s sign(\widehat{i_\alpha}) \\ e_\beta - k_s sign(\widehat{i_\beta}) \end{bmatrix}$$

Here, sgn(·) denotes the sign function, which introduces a discontinuity in the control action, creating robustness against disturbances and parameter variations. However, it leads to chattering, a primary drawback of SMO. The back EMF components are used to calculate the rotor position θ as:

$\theta = -\arctan(e_\alpha / e_\beta)$

C. Model Reference Adaptive System (MRAS)

The MRAS method compares the outputs of a reference model and an adjustable model. The difference (error) between the reference and adjustable models drives an adaptation mechanism to update the rotor speed and position estimates:

$$e(t) = i_{sd}^{\text{ref}} - i_{sd}^{\text{adj}}$$

where e(t) is the error between the d-axis stator current in the reference model and the adjustable model. The MRAS uses a proportional-integral (PI) adaptive law to minimize e(t):

$$\hat{\omega} = K_p e(t) + K_i \int e(t)\, dt$$

where ω^ is the estimated rotor speed, and Kp and Ki are tuning parameters for the proportional and integral gains. The estimated position is then obtained by integrating the estimated speed.

V. MODULAR DESIGN OF THE PROPOSED SYSTEM

D. PMSM Mathematical Model Module

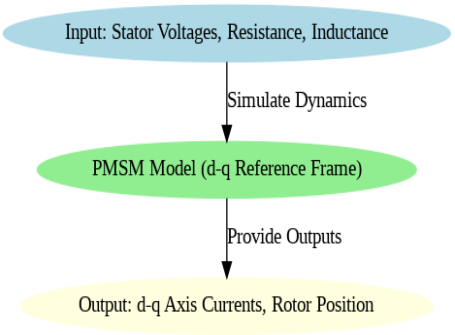


Figure 1. PMSM Mathematical Model Module

This module is there to simulate the dynamics of the Permanent Magnet Synchronous Motor in the d-q reference frame, which forms the core of sensorless control. This model is based on the voltage and torque equations derived from the mathematical approach to the PMSM. The inputs to the module are stator voltages, resistance, and inductance values. The module gives rotor position and d-q axis currents as outputs for a price. These are the outputs required further processing in the SMO and MRAS modules to estimate the rotor speed and position for sensorless control.

E. SMO Module

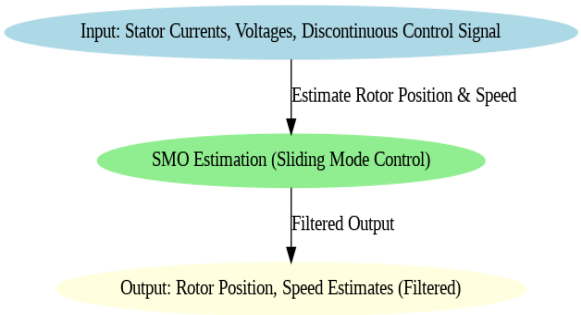


Figure 2. SMO Module

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Employ SMO module to estimate rotor position and speed using high-frequency switching with the underlying principles of sliding mode control. This approach ensures robust performance of the system, even in the presence of uncertainties within the system parameters. The stator currents and voltages, and a discontinuous control signal based on a sign function, are presented to maintain the sliding conditions for the operation of the SMO module. The rotor position and speed are supposed to be estimates given at the out of the SMO; these estimates are then filtered through a low-pass filter in order to minimize the effects of chattering. An important implementation consideration for this module is the observer gain, which must be tuned to a good compromise between estimation accuracy and chattering reduction.

F. MRAS Module

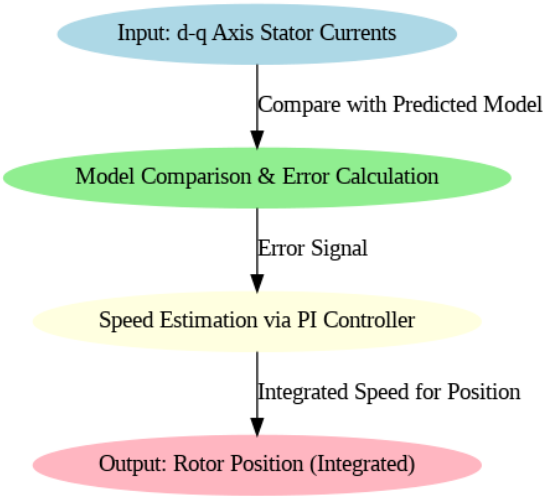


Figure 3. MRAS Module

The MRAS module is used for estimation of rotor speed and position by adapting a control law according to reference model. The computed stator currents in the d-q axis from the model of the PMSM are applied as inputs to the module. The module compares an actual current in the d-axis with the generated predicted current, based on a model that is adjustable, and produces a resultant error signal. The error signal is used by a PI controller for online update of rotor speed estimates, which is to be achieved through integration of its output to obtain rotor position. For proper functionality, the MRAS module was designed with Popov's hyper-stability criterion, so at least the stability of the module should be assured as is required irrespective of parameter variations in accordance with the adaptive law.

G. Simulation and Testing Module

The Simulation and Testing Module will offer an environment by which the performance of each observer method will be evaluated under a variety of operating conditions. The two approaches developed-namely, SMO and MRAS are verified with the help of MATLAB/Simulink and simulation. It is to be tested under the conditions of speed variation and load/ environmental disturbances, where some of the main performance criteria toward testing would include position estimation error, response time, and computational load. This module is a critical tool to understand, in depth, the strengths and weaknesses of every observer technique under various scenarios.

The PMSM parameters used for modeling and simulation are listed in Table-1.

Table 1: PMSM Parameters

Parameters	Values
Stator Phase Resistance (Ohms)	2.875
Armature Inductance (Henry)	0.00153
Flux Linkage (Wb)	0.175
Pole Pair	4
Viscous Damping (Nms)	5.28e-05
Moment of Inertia (kgm^2)	3.17e-05

H. Module for Performance Analysis

The module for performance analysis collects together results obtained from the Simulation and Testing Module in generating actionable insights on the performance of the various observer methods. It compares the SMO and MRAS, on a large set of testing scenarios to identify optimal configurations for each approach. The module provides deep-level performance analysis, based on various metrics such as accuracy, computational efficiency, and robustness. This becomes the benchmarking agent in order to figure out what further enhancements exist, for example, the minimization of chattering within the SMO or the improvement of response times within the MRAS. In addition, it gives data-driven recommendations for selecting the best observer method for different operating conditions that can prompt additional changes. The proposed control system is an adaptive sensorless method for PMSMs control in electric vehicles. It integrates robustness inherent in Sliding Mode Observer with accuracy derived from Model Reference Adaptive System. Simulation and testing of these techniques in a modular framework will constitute the core of the project, providing a basis for hybridization of the two methods on exploiting each other's strengths. Improvement in the accuracy of rotor position estimation as well as improved computational efficiency are expected outcomes coupled with an adaptive control strategy capable of adapting to varying operating conditions. Ultimately, this design approach aims for substantial advancements in both performance and robustness of EV motor control systems for reliable and efficient solutions whenever used in sensorless configurations.

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VI. RESULTS AND DISCUSSION

SMO: Real Angle vs Estimated Angle

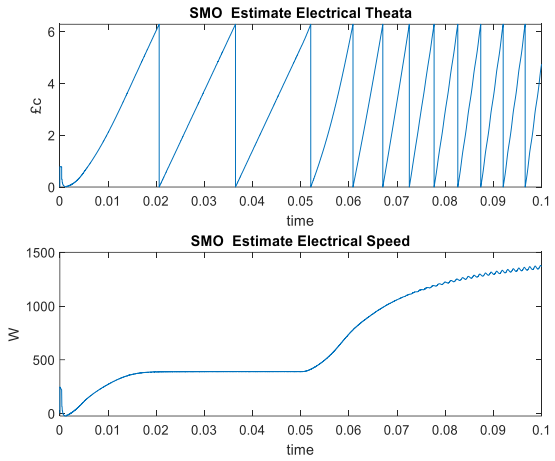


Figure 5. SMO

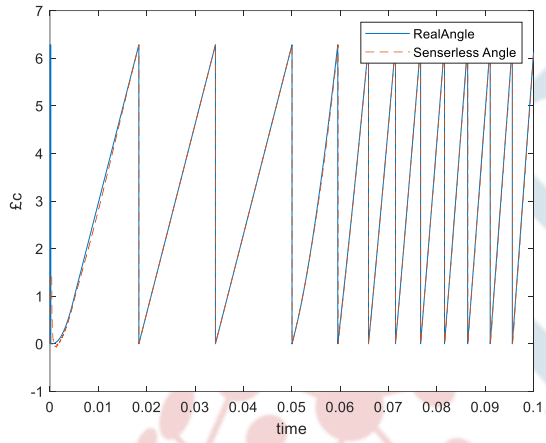


Figure 6. SMO Real angle vs Estimate angle

The simulated results of the Sliding Mode Observer (SMO) are represented as comparison between the real rotor angle and the estimated rotor angle. The plot is demonstrated showing the performance of the SMO in estimating rotor angles under various operating conditions. Real angle was derived from the mathematical model of the PMSM, while the estimated angle was obtained from the module of SMO. Comparing, it is observed that the SMO can accurately track the real value of rotor angles with minor deviations occurring primarily under dynamic transitions or sudden changes in load. However, the SMO can keep track of an estimate for the rotor angle within a reasonable error bound for sensorless control. The minor difference between the actual and estimated angles is due to the chattering effect inherent to the sliding mode control and can be minimized using proper filtering techniques. While this is the case, the SMO yields reasonably accurate angle estimation, and hence it is a good candidate for sensorless motor control especially in applications where immunity to disturbances is critical.

MRAS: Real Angle vs Estimated Angle

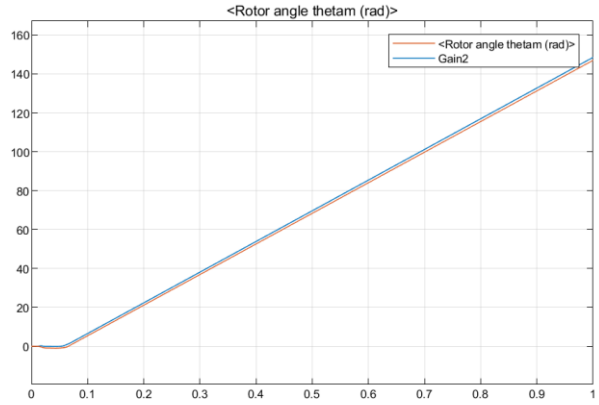


Figure 7. MRAS Real angle vs Estimated angle

For example, the rotor angle obtained through comparison between the actual and measured rotor angles is pretty accurate for the estimation of the rotor position. MRAS uses an adaptive control law to compare the actual d-axis current with the predicted value of d-axis current from the adaptive model to update the rotor speed and position estimates.

The plot shows that the MRAS returns reasonably accurate angle estimates of the rotor with minimal errors even under varied operations. The small estimation errors were largely due to a parameter mismatch or disturbance effects on adaptation. This can be attributed to effects of disturbances or mismatches in parameters against adaptation in the model. Though the SMO has mild accuracy in estimating the angle of the rotor, the MRAS showed significant accuracy for applications that demand high degree position tracking.

The results underpin the flexibility of the MRAS as it learns with changing conditions; this will more precisely estimate than SMO, primarily on steady-state conditions. However, the increased computational complexity justifies the accuracy levels.

MRAS: Estimated Electrical Speed

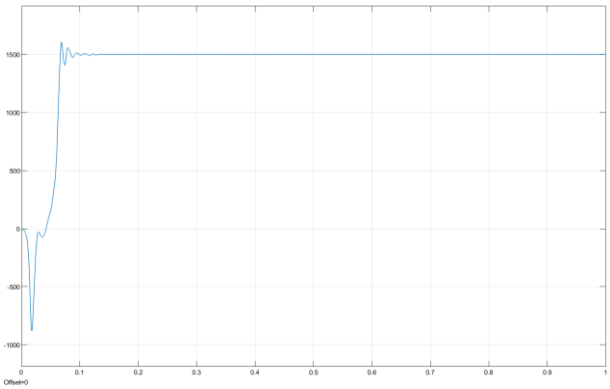


Figure 8. MRAS estimate electrical speed

Except for rotor position estimation, the MRAS also outputs electrical speed estimation. The simulation results of the MRAS electrical speed estimator for a given PMSM

motor are shown, in an attempt to indicate how much the estimated speed tracks the real electrical speed of the PMSM. The estimated speed will be obtained through integration of the rotor speed retrieved by the PI controller in the MRAS.

The plot depicts that the MRAS is highly effective in tracking the actual electrical speed; and during the simulation, the estimated speed closely follows the actual speed. Even due to the small deviations between the estimated and actual electrical speed, due to transient effects or slight model inaccuracies, however, the MRAS does deliver pretty accurate and consistent speed estimates.

These results demonstrate that MRAS is appropriate for the applications that require precise speed control, especially in varying load conditions or operating points. The accurate speed estimation of the MRAS entails that the fact that it provides ensures its potentiality as a useful tool for sensorless control with a higher performance in comparison to other methods, such as SMO.

VII. CONCLUSION

From the simulation plots, it can easily be concluded that both SMO and MRAS are valid and viable means for sensorless control of PMSMs but with a big difference as to either robustness and efficiency of angle estimation through SMO or precision in the estimation of rotor angle and electrical speed through MRAS. The drawback is that MRAS introduces additional computational load in comparison to the more computationally friendly SMO. These results clearly highlight the selection of appropriate observers for specific applications and further possible integration of both approaches into one hybrid control system.

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