MRAS Speed Estimator for a PMSM Machine: Practice Design

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ABSTRACT

Wind energy systems are based on synchronous machines, which can support high-speed rotation cases due to possible high-speed values of incoming winds. The machines used are affiliated with permanent magnet machines, whereas speed detection can become difficult. This complication appears when high incoming wind speed values increase the motor temperature, which in turn can influence motor parameters, and especially the stator resistance. This can impact the proposed speed software estimator robustness. The proposed high-speed estimator algorithm is based on the Model Reference Adaptive System (MRAS) estimation method, which can be used for motor speed estimation. This concept includes the reactive power model, which ensures the robustness of the estimator when facing any possible stator resistance variation, even at very high speeds.

Keywords-MRAS; speed; machine; estimation

I. INTRODUCTION

Different rotor positions and speed values of sensorless control can be found in the literature, as this type of control is being based on the artificial intelligence [1], sliding-mode observer [2] or Model Reference Adaptive System (MRAS). The efficiency of these software speed encoders is presented in the cited work in specific conditions and on a specific speed zone. However, the verified robustness was proved under specific speed ranges, which do not consider the high-speed range.

High-speed rotating electrical machines are critical in several advanced applications, where rapid rotational speeds lead to improved efficiency and performance. One notable such application is in the aerospace industry, where high-speed motors are used in jet engines and auxiliary power units. These motors provide the necessary thrust and power with minimal weight and space, making an aircraft lighter and more fuel-efficient. Another significant use is in the electric and hybrid vehicles, where high-speed motors enhance acceleration and overall performance while maintaining compact size and reduced weight. Additionally, high-speed electrical machines are essential in industrial processes, such as high-frequency spindle drives in CNC machines and turbo compressors, where precision and speed are paramount for productivity and quality. The medical field is also benefited from high-speed motors in devices like dental drills and surgical tools, where precision, control, and speed are crucial for effective treatment. The interest in high-speed rotating electrical machines stems from their ability to deliver high power density, leading to smaller, lighter, and more efficient systems. This characteristic is particularly beneficial in applications where space and weight constraints are critical, such as in aerospace and automotive industries. Furthermore, high-speed motors typically exhibit lower energy losses, resulting in better overall efficiency and reduced operational costs. The ability to operate at high speeds also enables these machines to handle dynamic and demanding tasks more effectively, improving performance and reliability across various applications [3-4].

Sensorless speed observation for Permanent Magnet Synchronous Motors (PMSM) encompasses a range of advanced methods, techniques, and intelligent solutions aimed at achieving precise and reliable speed estimation without the need for physical sensors. Among these methods, MRAS have gained significant attention due to their robustness and accuracy. MRAS-based observers typically employ a reference model and an adaptive model to estimate the motor speed, adjusting parameters to minimize the error between the models. Other techniques include Extended Kalman Filters (EKF), Sliding Mode Observers (SMO), and Artificial Intelligence (AI)-based approaches including Neural Networks and Fuzzy Logic. EKF provides optimal estimation by accounting for system noise and uncertainties, while SMO offers high robustness against parameter variations and external disturbances. AI methods leverage Machine Learning (ML) algorithms to adaptively predict motor speed, enhancing performance in dynamic conditions. Collectively, these advanced techniques enable efficient, cost-effective, and high-performance control of PMSMs in various industrial applications.

MRAS are widely deployed in sensorless speed observation for PMSM for several compelling reasons. Initially, MRAS offers high robustness and accuracy in speed estimation. By continuously adapting the model parameters to minimize the error between the reference and adaptive models, MRAS can achieve precise speed estimation even in the presence of system uncertainties and external disturbances. The MRAS approach is relatively straightforward to implement compared to other advanced techniques like EKF. The mathematical formulation of MRAS is less complex, making it easier to be designed and integrated into existing control systems. MRAS can operate effectively in real-time, which is critical for the dynamic control of PMSMs. The adaptive nature of MRAS allows it to respond quickly to changes in motor speed and load conditions, ensuring stable and efficient motor performance. MRAS can be easily integrated with different control schemes, such as Field-Oriented Control (FOC) and Direct Torque Control (DTC), enhancing its versatility in various applications. This compatibility renders MRAS a preferred choice for a wide range of industrial applications [5]. Implementing MRAS does not require additional hardware, such as sensors, which reduces the overall cost of the motor control system. This cost-effectiveness, combined with its robust performance, makes MRAS an attractive solution for many applications. MRAS can adapt to changes in motor parameters and operating conditions. This adaptability ensures that the speed observer remains accurate over time, even as the motor characteristics change due to factors like temperature variations and aging. Overall, the combination of robustness, simplicity, real-time performance, compatibility, cost-effectiveness, and adaptability makes MRAS a popular and effective solution for sensorless speed observation in PMSMs [6].

PMSM can be operated at high-speed zones and can reach up to 200% of the rotor speed [3]. This can be assured if the filed weakening mode is activated. Due to this special running mode, many parameters, especially the magnetic flux and the stator resistance variable, can be altered. These parameter variations would normally affect the sensorless speed mathematical model, influencing system stability, effectiveness, and robustness [7]. This test condition is required in many applications that use high-speed regions. In the case of wind system applications, some systems can exceed the nominal speed motors in an overtaken phase or other possible conditions. Then, the system's dysfunction will be out at this stage, and the overall loop will be out.

The current study presents an efficient software speed encoder based on a robust MRAS technique that can be operated at high speeds. On the other hand, for an MRAS estimator, the Popov criterion is used based on a PI controller that needs to be adapted to the system configuration. In order to avoid complications related to the nonlinearity of the studied system on the MRAS adaptation algorithm [6] the POPOV criterion is adapted to the Particle Swarm Optimization (PSO) algorithm.

II. PERMANENT MAGNET MACHINE

This paper aims to identify the best control method while maintaining motor security and capturing speed goals. Based on our previous study, the concept of field weakening can be used to resolve the high-speed running phenomenon [8-10].

The idea behind this technology is comparable to that of a DC machine, in which the flux can be controlled separately. Therefore, achieving a high-speed region requires flux minimization. The flux generated by the rotor magnet (λm) poses as a challenge to minimize the overall motor flux. Generally speaking, maintaining a zero direct stator current ensures the rated speed mode [6]. The direct flux component must be decreased to influence the high-speed mode, according to the flux formulas shown in (1) by lowering the direct stator component to the negative zone.

$$\begin{cases} I_d^2 + I_q^2 \leq I_{max}^2 \\ V_d^2 + V_q^2 \leq V_{max}^2 \end{cases} \tag{1}$$

Equation (3) exposes this expression. This relation was depicted from the voltage equation model as it is presented in (2). Supposing that the saturation effect is null and that the hysteresis iron loss is absent, it will be able to expose the high-speed control loop, which will calculate the necessary direct stator current component.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega L_d \\ \omega L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\lambda_m \end{bmatrix} \tag{2}$$

$$i_d^* = \frac{\sqrt{V_{max}^2 - (\omega L_q i_q)^2} - \omega\lambda_m}{\omega L_d} \tag{3}$$

III. MRAS-REACTIVE POWER SPEED OBSERVER

The MRAS reactive power estimator model is crucial for enhancing the precision of speed observers in Permanent Magnet Synchronous Motors (PMSMs). This model leverages the relationship between reactive power and motor speed to provide accurate and reliable speed estimation. By using reactive power as a reference, the MRAS estimator can effectively compensate for variations and disturbances that commonly affect motor performance, such as changes in load conditions or parameter variations. This approach improves the observer's ability to maintain precise speed estimation, ensuring stable and efficient motor control. Furthermore, the MRAS reactive power estimator enhances the overall robustness of the speed observer by adapting to real-time operating conditions, minimizing the impact of external disturbances, and reducing estimation errors [11-12]. This results in improved performance in dynamic environments and contributes to the high accuracy required for advanced industrial applications, making it an essential component in the sensorless control of PMSMs.

One type of efficiency estimation methodology is the model reference adaptive system technique. This method can be considered the most proficient one when compared to the Back-EMF and state observer methods [1]. Some authors link this approach to intelligent estimating techniques found in other literature works, where fuzzy and neural solutions may also be appealing. Nevertheless, the drawbacks of these systems is the inadequacy to comprehend database information [13]. As a result, the majority of published research is based on techniques that employ mathematical models, such as MRAS, Lunberger, etc., highlighting the effectiveness of the suggested solutions ([14-16].) The "reference" and "adjustable" mathematical models, evidenced in Figure 1, form the foundation of the MRAS principle.

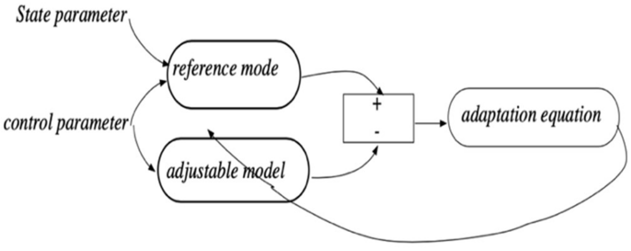

Fig. 1. General design of the MRAS.

$$Q_s = \omega\left(L_d i_d^2 + L_q i_q^2\right) + \left(L_d i_d^2 \frac{di_q}{dt} - L_q i_q \frac{di_q}{dt}\right) + \omega i_d \lambda_m \quad (5)$$

In the permanent regions, where the torque and the motor speeds are constant, it is possible to migrate (5) to (6), where all currents are supposed to be constant.

Utilizing as a base the stator currents, which will act as the direct and transversal components, the emerging adjustable Q-MRAS model is illustrated in (7).

$$Q_s = \omega\left(L_d i_d^2 + L_q i_q^2\right) + \omega i_d \lambda_m \quad (6)$$

$$\widehat{Q_s} = \widehat{\omega}\left(L_d \widehat{i_d^2} + L_q \widehat{i_q^2}\right) + \widehat{\omega}\widehat{i_d}\lambda_m \quad (7)$$

IV. STABILITY ANALYSIS OF THE REACTIVE POWER MRAS ESTIMATOR

Analyzing the stability of the MRAS speed observer is crucial because it ensures reliable and consistent performance in controlling PMSMs. Stability analysis helps in understanding how the observer reacts to different operating conditions and disturbances, providing insights into its robustness and accuracy over time. A stable MRAS speed observer guarantees that the estimated speed converges to the actual motor speed without oscillations or divergence, which is vital for precise motor control. By examining stability, engineers can identify potential weaknesses in the observer design, optimize adaptive parameters, and enhance the system's resilience to parameter variations and external disturbances. This analysis is particularly important in industrial applications, where PMSMs are subject to varying loads and environmental conditions, ensuring that the motor operates efficiently and safely. Overall, the stability analysis of the MRAS speed observer is the key to achieving high-performance, reliable, and efficient sensorless motor control.

The Q_MRAS scheme can be represented by this simple control loop, as presented in Figure 2. The PI controller is used to adjust the speed of a G(s) system. The PI input signal is defined by the error between the real and the estimated reactive power as expressed in (8) as follows [17-18]:

$$e_q = Q_s - \widehat{Q_s} = v_q(i_d - \hat{\imath}_d) - v_d(i_q - \hat{\imath}_q) \quad (8)$$

The stability analysis was applied in different speed zones, starting from 5000 rpm, with the maximum speed being supported by the used motor. Figure 3 presents the obtained Nyquist graph.

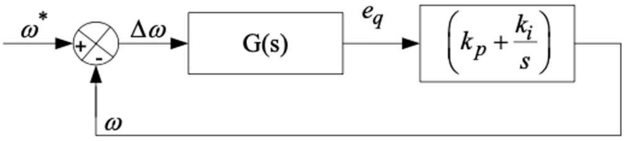

Fig. 2. Simplified control loop of Q_MRAS.

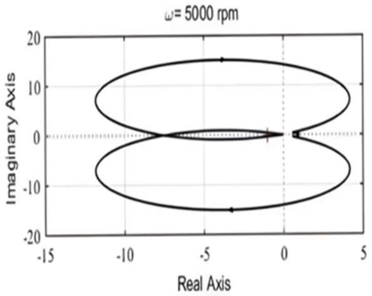

Fig. 3. Nyquist Map for the Q_MRAS speed observer under different speeds.

The results demonstrate the stability of the speed observer under high-speed variation. These results guarantee the overall observed system stability.

V. RESULTS

In this section, the experimental bank utilized to validate the high-speed control loop is presented. The global material group can be observed in Figure 4. Basically, the PMSM is related to a compressor system, which can reach very high speed values by injecting a high-pressure oil to simulate high-speed regions. The specifications of the electrical machine can be seen in Table I.

TABLE I. ELECTRICAL MACHINE PARAMETERS

Motor Type	2AML406B-090-10-170
Manufacture	VUES Brno
Nominal Speed	25000 rpm

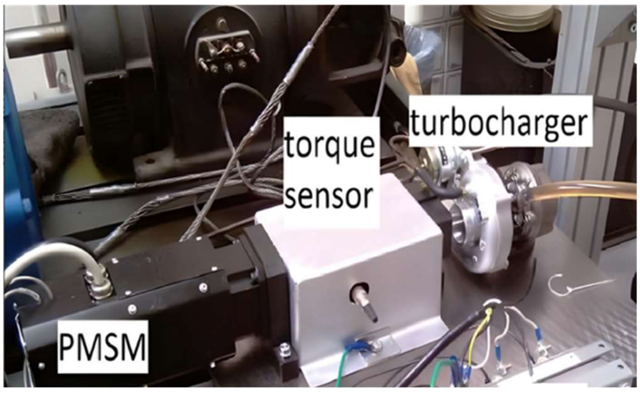

Fig. 4. Utilized hardware.

In the hardware implementation (Figure 4), a vector control strategy coupled with the software speed encoder is used to control the machine. As it was explained in the previous section, the speed software encoder called Q-MRAS requests a lot of motor information, namely currents and tensions in the (d, q) frame. Those signals are obtained from ADC blocs inserted in the control card. The principles of the vector control method are portrayed in Figure 5, where the direct voltage is approximately negative. The vector principle and high-speed theory are verified. The existing ripples in those variables are related to the inverter model, which is characterized by 15 MHz as a commutation variable. If the inverter frequency is higher than 15 MHz, then the ripples number decreases. Furthermore, the efficiency of the global loop performance is demonstrated under two conditions: the given reference speed is equivalent to 32000 rpm (650 Hz) and the given load torque decreases proportionally. That is, at $t = 0.01$ s with Te=1.2 N m and at $t = 0.06$ s with Te=1 N m. The results are illustrated in Figure 6. The real speed follows the estimated one, with the excessive noise of the latter starting at $t = 0.04$ s.

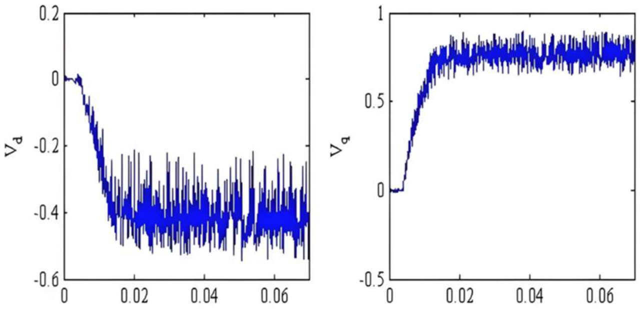

Fig. 5. Currents and voltage results.

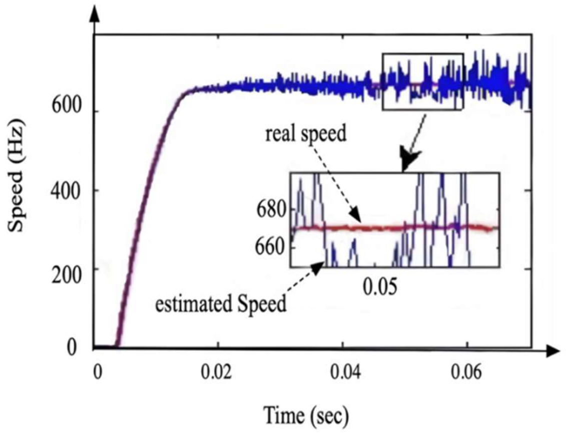

Fig. 6. Speed performance (Hz). The real speed is shown in red color and the estimated speed in blue.

VI. CONCLUSIONS

The Permanent Magnet Synchronous Motors (PMSM) control without a speed encoder is implemented in this study. The Model Reference Adaptive System (MRAS) ensures the speed encoder's efficiency after adjusting its PI controller by employing the PSO tool, which is based on reactive power characteristics. The vector control technique is deployed to ensure effective motor control, and the High Speed Algorithm is used while operating in this mode. The selection of the speed observer is based on the robustness of the speed estimation tool phase and the motor parameter variation as the stator resistance. From the other side, and in relation to the specification of the wind system, which faces high speed regions due to high wind speed, the motor speed observer has to be efficient enough in that speed characterization.

The work on electrical motor speed estimation is pivotal in enhancing the efficiency and performance of various industrial and consumer applications. The primary objective of this research was to develop accurate and reliable methods for estimating the speed of electric motors, which are essential components in numerous systems, such as automotive engines, manufacturing machinery, and household appliances. The focus was on exploring both hardware and software solutions to achieve high precision in speed estimation. One approach to accomplish this involves the use of advanced sensor technologies, such as encoders and tachometers, which directly measure the rotational speed. However, these sensors can be expensive and prone to wear and tear, making them less ideal for long-term use. Therefore, another perspective is the implementation of sensorless techniques, which utilize algorithms and signal processing methods to estimate speed based on electrical parameters like current and voltage. These methods are cost-effective and reduce maintenance requirements, but they demand sophisticated computational resources and robust algorithms to handle various operational conditions and disturbances [19]. The integration of Machine Learning (ML) and Artificial Intelligence (AI) presents a promising avenue for improving the accuracy and adaptability of sensorless speed estimation. By training models on extensive datasets, the system can learn to predict motor speed with high precision even under dynamic conditions [20]. Ultimately, this research aims to balance the trade-offs between cost, reliability, and accuracy, providing a comprehensive solution for electric motor speed estimation that can be widely adopted across different industries. The outcomes of this work have the potential to significantly enhance motor control strategies, leading to a more efficient and sustainable use of electrical energy.

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