Sliding Mode Predictive Control using Model Reference Adaptive System of Permanent Magnet Synchronous Motor

IBRAHIM FAROUK BOUGUENNA[1,*], SAID BENKAIHOUL[2],
MOHAMMED BENMADANI DEBBAT[1,3], ABDELGHANI ZABEL[1], TAHOUR AHMED [1]
[1]Electrotechnical Department, University of Mascara,
Mascara 29000,
ALGERIA

[2]Electrical Engineering Department,
Ziane Achour University,
P. O. B. 3117, 17000 Djelfa,
ALGERIA

[3]Catalonia Institute for Energy Research, Barcelona,
SPAIN

Abstract: - This paper explores the implementation of a Sliding Mode Predictive Control (SMPC) strategy using a Model Reference Adaptive System (MRAS) for a Permanent Magnet Synchronous Motor (PMSM). The study aims to achieve accurate speed tracking and reduced torque ripple in PMSMs using SMPC and MRAS. The model predictive control depends on estimating the prediction currents to obtain the voltage vectors to control the inverter pulses. Further, by using the cost function the selection of the best voltage conductor is obtained. The disturbance in the PI controller affects the speed efficiency, so a sliding mode is added to reduce the speed disturbance and get a better convergence. Therefore, the speed of the machine extracted from the sensor remains unacceptable, and to enhance the results, MRAS is used to estimate the new speed. Simulation results indicate that the proposed control approach effectively improves the performance of the PMSM in terms of both speed regulation and torque ripple reduction. The findings of this study offer significant insights into the potential of SMPC with MRAS as a control strategy for PMSMs in various industrial applications.

Key-Words: - Permanent Magnet Synchronous Motor, Model Predictive Control, MRAS, Sliding Mode Control, PI Controller, Speed, Torque.

Received: May 16, 2024. Revised: November 8, 2024. Accepted: December 11, 2024. Published: February 3, 2025.

1 Introduction

Permanent Magnet Synchronous Motors (PMSMs) have been extensively studied over time because these motor configurations are omnipresent in industrial applications due to their reliable performance, high efficiency during operation, low sound, and superior control during operation. Therefore, PMSM motors are always utilized in the background for anything from electric cars to industrial automation to the motors used for generating renewable energy, [1], [2], [3].

This motor is characterized by high power density, high torque-to-inertia ratio, and a simplified construction scheme usable across various environments. Moreover, an artificially configured induction motor of like configuration provides less efficiency and not as effective dynamic response compared to a PMSM, [4].

The past years have seen a rise in many different control methods to optimize PMSM such as Field Oriented Control (FOC) , Direct Torque Control (DTC) [5], Sliding Mode Control (SMC) [6], Model predictive control (MPC) [7], [8], [9] and Adaptive Control, [10]. Yet control methods from the past such as Proportional-Integral-Derivative control have been established for some time and are not successful in controlling permanent magnet synchronous motors. For instance, the PID is ineffective because the dynamics of the system are highly nonlinear with parameter uncertainties and external disturbances. Yet one type of control that is contrary to this is called Model Predictive Control, which is a control method that considers a mathematical model of the process to predict future responses and thus imposes suitable control efforts within a finite control horizon, [11], [12], [13].

Compared to conventional control strategies, MPC can take care of barriers on top of things inputs and device outputs, ensuring the secure operation of the machine. The MPC is likewise greater robust and adaptable for different working conditions, capable of taking care of parameter uncertainty and external disturbances. Recent research has proven the effectiveness of MPCs on numerous applications of PMSMs together with electric automobiles, wind turbines, and robots, [14], [15], [16].

Model predictive control strategy (MPC) and observer-based total control techniques have emerged as famous methods for controlling PMSMs. MPC is a command technique that uses the dynamic model of the device to expect the future behavior of the device and generates control inputs accordingly. This allows MPC to handle system nonlinearities and disturbances extra effectively. Studies have shown that MPC can manipulate PMSM. For example, in reference [17], researchers present an MPC-primarily based control scheme for PMSM which progressed accuracy and robustness below special running situations, and in [18], the authors used a modified MPC set of rules to improve the control speed of PMSM and accuracy. Direct torque with a modified MPC was delivered [19] to reduce the torque wave and glaringly advanced the robustness of the system. Fault-tolerant control strategy based on Finite Control Set MPC (FCS-MPC) with kalman filter, [20]. The proposed technique combines the Model Predictive Control (MPC) for the speed and current control loops, and an almost error-free Unscented Kalman Filter (UKF) to estimate the PMSM inter-turn fault ratio. Authors in [21] proposed a Nonlinear MPC (NMPC) to suggest different sampling times in the prediction process and increase the prediction horizon. DTMPC has been extensively used due to its simplicity and good performance. FCS-MPC is a more recent approach that reduces the computational burden of DTMPC by using a smaller control set, [22]. In [23], a control scheme utilizing fuzzy logic in conjunction with a multi-vector finite-control-set model predictive control (MV-FCS-MPC) approach. In reference [24] the authors propose a nonlinear model predictive speed control (NMPSC) with prediction horizon self-tuning method applied to a permanent magnet synchronous motor (PMSM) rotor position. In [25], [26], an adaptive integral sliding-mode predictive control (AISMPC) and Advanced Dual-Loop Control have been designed to control the speed and the current of the PMSM.

Replacing the traditional PI controller with a sliding mode controller (SMC) for the speed loop of PMSM has been proposed in this paper due to its performance and robustness. The proposed SMC approach provided a better dynamic response with less overshoot and shorter settling time compared to the PI controller. This new approach demonstrated better tracking accuracy and robustness in the presence of load disturbances and parameter uncertainties.

Observers are feedback control strategies which provide estimates of the states of the system from the available measurements. They can be updated on disturbances and improve supervision of entire performance. In PMSM control, many observers are used to estimate the rate. Of these, the most commonly used observer is the Extended Kalman Filter (EKF) in [27]. This observer is constructed based on the mathematical model of the PMSM and is able to accurately estimate the rotor velocity and position. In addition, [28] proposed the second type of observer used for velocity estimation, known as the Sliding Mode Observer (SMO).

The SMO itself is insensitive to the structure parameters versions and external disturbances of the entire system. Alongside the EKF and SMO, the High-Gain Observer (HGO) has been applied to PMSM manipulation for speed estimation. The HGO transitioned to the proposed in [29] and has the advantage of being simpler and stronger than other observers. The Adaptive Observer (AO) proposed in [30] is another observer used for velocity estimation used in the PMSM command. AO can estimate the speed and if rotor operate normally regardless of unknown load disturbances. Moreover, in [31] the Unknown Input Observer (UIO) has been proposed in combination with definition for PMSM command used for speed estimation. Unknown disturbance does not affect the UIO-based estimation rate.

Thus, MPC and Observers have been used in conjunction to control PMSM to improve both performance and robustness of the device. Mixed strategies: MPC and Observer type, integration of DTMPC with EKF, FCS-MPC with SMO and NMPC with HGO. The integrated methods are able to manage limitations, uncertainties, and nonlinearities of the PMSM device while at the same time imparting accurate estimation. The model reference adaptive system (MRAS) is one of the well-known approaches for the sensorless velocity control of PMSMs. MRAS is a model reference adaptive system which estimates the rotor state and speed of the motor using the input of stator currents and voltages. The important advantage of the MRAS method is that it may offer accurate velocity estimation without requiring additional hardware sensors, which can lessen the fee and complexity of regulating the motor. Many researchers have studied the software program of MRAS in PMSM control. For example, authors in [32] proposed an MRAS-based completely pace estimation approach for PMSMs that makes use of an excessive-frequency signal injection method to improve the accuracy of the estimation. In [33] advanced strategy was proposed involving an adaptive observer based on MRAS to estimate the rotor speed of a PMSM within the presence of parameter variations and burden disturbances. Another study by [34] introduced an MRAS-primarily based method for estimating the rotor velocity and position of a PMSM with a hybrid excitation shape. Overall, MRAS is an extensively used approach for sensorless velocity regulation of PMSMs. Its capacity to appropriately estimate the rotor speed and function without requiring additional hardware sensors makes it an appealing option for plenty of business applications.

The present paper targets to explicate the attributes and contributions of Sliding Mode Predictive Control (SMPC) that employs Model Reference Adaptive System (MRAS) for Permanent Magnet Synchronous Motor (PMSM) drives. The limitations of the Proportional Integral-Model Predictive Control (PI-MPC) technique, when implemented on PMSM, can be overcome by substituting the PI controller in the outer loop with a sliding mode controller, which results in reduced speed disturbance and enables better convergence. Furthermore, augmenting the SMPC with MRAS leads to a significant improvement in the PMSM's performance with respect to both speed regulation and reduction of torque ripple.

This paper is structured as follows. Firstly, Section 2 introduces the mathematical model of Permanent Magnet Synchronous Motor (PMSM) and Model Reference Adaptive System (MRAS). Subsequently, Sections 3 and 4 outline the development of the SMPC-MRAS framework. Furthermore, Section 5 presents the simulation results that effectively demonstrate the efficacy of the proposed approach. Finally, Section 6 succinctly summarizes the key findings and conclusions of this study.

2 Modeling MRAS of PMSM

The PMSM mathematical model is represented by currents id and iq, and the final form of the torque equation is as follows [35], [36]:

$$\begin{cases} \frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + w_r i_q + \frac{u_d}{L_d} \\ \frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - w_r i_d - \frac{\phi_f}{L_q} w_r + \frac{u_q}{L_q} \\ T_e = \frac{3}{2} p \, \phi_f \, i_q \end{cases} \tag{1}$$

In the dq reference frame, stator voltages (u_d, u_q) and stator currents (i_d, i_q) are represented in volts and amperes, respectively. The stator resistance (R_s) is measured in ohms. L_d and L_q represent the inductance of the direct and quadrature axes, respectively, with both measured in henry. w_r represents the electrical speed of the rotor in radians per second, and p corresponds to the pole-pair number. Electromagnetic torque (T_e) is measured in Newton meters [N.m]. Φ_f permanent magnet flux linkage.

The Model Reference Adaptive System (MRAS) constitutes a monitoring technique premised on the principle of stability. Its operational modality is predicated on three fundamental components, namely the reference model, adjustable, and adaptive mechanism, as illustrated in Figure 1. This technique finds utility in the estimation of both the speed and angle of the rotor, [37], [38].

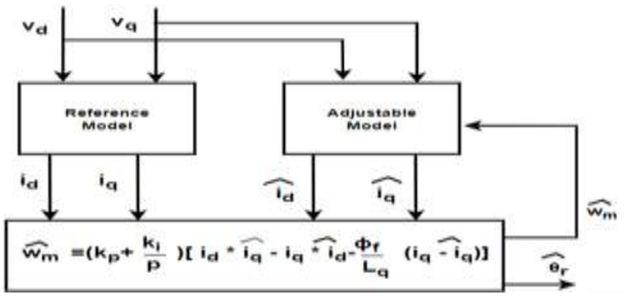

Fig. 1: schematic Block of MRAS

In the adjustable part, the currents $\widehat{i_d}$ and $\widehat{i_q}$ are generated using equations 1, but with the presence of the speed estimate $\widehat{w_r}$ derived from the adaptive mechanism.

$$\begin{cases} \frac{d\widehat{i_d}}{dt} = -\frac{R_s}{L_d} \widehat{i_d} + \widehat{w_r} \widehat{i_q} + \frac{u_d}{L_d} \\ \frac{d\widehat{i_q}}{dt} = -\frac{R_s}{L_q} \widehat{i_q} - \widehat{w_r} \widehat{i_d} - \frac{\phi_f}{L_q} \widehat{w_r} + \frac{u_q}{L_q} \end{cases} \tag{2}$$

The expression for the speed estimate generated by the adaptive mechanism is as follows, [39]:

$$\widehat{w_m} = (k_p + \frac{k_i}{s})[i_d \widehat{i_q} - i_q \widehat{i_d} - \frac{\phi_f}{L_q}(i_q - \widehat{i_q})] \tag{3}$$

Where k_p, k_i are the coefficients of the regulator PI.

3 Sliding Mode Control

Sliding mode control is a robust control methodology well suited for application in the speed outer loop of permanent magnet synchronous motors (PMSMs). Its use complements overall performance and resilience, even in the presence of uncertainties and disturbances.

The sliding mode strategy is a sturdy control technique designed to overcome parameter modifications, versions, and disturbances. Permanent magnet synchronous motors (PMSMs) are susceptible to variations in motor parameters such as resistance, inductance, and rotor inertia. But regardless of those variations, the sliding mode can provide reliable overall performance of the system followed by an accurate control of the velocity. This control strategy shows rapid transient response and settling time, rendering it well-ideal for applications requiring precise and short speed control, along with high-overall performance drive structures and robotics. The sliding mode method would help the algorithm to handle the PMSM nonlinearities and maintain overall performance stable and precise regulation.

To develop the sliding mode control in the speed outer loop of a PMSM, some steps are required: * Formulate a mathematical model of the PMSM which represents its electrical and mechanical dynamics. Second, it is necessary to describe a sliding region that represents the motion of the drive system to achieve the desired response. The sliding region is a mathematical equation that characterizes the connection between the system states and control inputs. In the velocity outer loop, the sliding surface is generally defined in terms of the desired velocity reference and the actual velocity of the motor. Finally, a control law that propels the system states towards the sliding surface should be designed. The control law typically comprises the reaching law and the sliding mode control law, [40], [41].

The equation of the sliding surface is determined according to the equation of the speed error.

$$s(t) = e(t) = w_{mref}(t) - w_m(t) = 0 \quad (4)$$

By deriving Equation 4 and substitution in Equation 6, we obtain the derivative of the slip equation as show in Equation 7.

$$\dot{s}(t) = \dot{w}_{mref}(t) - \dot{w}_m(t) \quad (5)$$

$$\frac{dw_m}{dt} = \frac{1}{J}\,(T_e - T_L - F\, w_m) \quad (6)$$

$$\dot{s}(t) = \frac{1}{J}(-\frac{3}{2}\, p\, \phi_f\, i_{qref} + T_L + F\, w_m) \quad (7)$$

T_L in N.m is the mechanical load torque applied. J and F are the rotor inertia in kg/m^2 and the viscous friction coefficient in N.m.s respectively.

To calculate the reference current i_{qref}, the SMC characteristic using Equation 8.

Where the current i_{qeq} was calculated from Equation 7 with $\dot{s}$ = s = 0

As for the current i_{qm}, it is related to the discontinuous part, as in the equation 10, to obtain the reference current equation as follows:

$$i_{qref} = i_{qm} + i_{qeq} \quad (8)$$

$$i_{qeq} = \frac{2(T_L + F\, w_m)}{3\, p\, \phi_f} \quad (9)$$

$$i_{qm} = k_1 * sign(e) + k_2 * e \quad (10)$$

$$i_{qref} = k_1 * sign(e) + k_2 * e + \frac{2(T_L + F\, w_m)}{3\, p\, \phi_f} \quad (11)$$

Where k_1, k_2 are SMC gains

4 Finite Control Set Model Predictive Control

In this study, a generally utilized three-stage source inverter is joined with a PMSM, as shown in Figure 3 (Appendix). The inverter incorporates eight specific trading vectors, resulting in the production of eight voltage vectors, namely u_0 - u_7. Among these, six are nonzero vectors while the remaining two are zero vectors. The size of the dynamic voltage vectors inside the fixed reference frame *alpha-beta* is presented in Figure 2 and Table 1. In order to devise the conventional FCS-MPC approach, it is crucial to employ a discrete-time model for predicting future currents. To achieve this, we employ the forward Euler technique on the continuous-time model, using a testing time span T_s [in seconds]. For $T_s << 1$, the subsequent equation is valid: $x(k) = x(kT_s) \approx x(t)$ and $\frac{d}{dt}x(t) = \frac{x(k+1)-x(k)}{T_s}$ for all $t \in [kT_s,(k+1)T_s]$ and $k \in \mathbb{N} \cup \{0\}$. As a result, the PMSM's discrete-time representation in the pivoting *dq*-reference casing can be communicated as follows:

$$\begin{cases} i_d(k+1) = \left(1 - \frac{R_s T_s}{L_d}\right) i_d(k) + T_s\, w_r\, i_q(k) \\ \qquad \frac{T_s}{L_d}\, u_d(k) \end{cases} \quad (12)$$

$$\begin{cases} i_q(k+1) = \left(1 - \frac{R_s T_s}{L_q}\right) i_q(k) + T_s\, w_r\, i_d(k) \\ \frac{T_s}{L_q}\, u_q(k) - \frac{\phi_f\, T_s}{L_q}\, w_r(k) \end{cases} \quad (13)$$

The cost function is used to evaluate the seven expected voltage vectors in Figure 2 during the sampling period, and the lowest cost function is chosen.

$$g=|i_{dref}(k+1)-i_d(k+1)\, u_{0,..,7}| + |i_{qref}(k+1)-i_q(k+1) u_{0,..,7}| + \begin{cases} 0 & if\ \sqrt{i_d(k+1)^2 + i_q(k+1)^2} \le I_{max} \\ \infty & if\ \sqrt{i_d(k+1)^2 + i_q(k+1)^2} \ge I_{max} \end{cases} \quad (14)$$

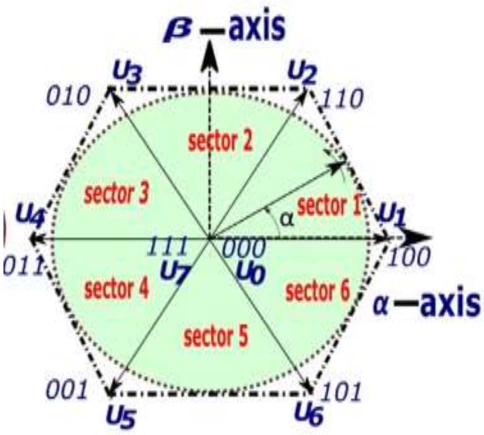

Fig. 2: Voltage vector diagram in α-β frames

Voltage vectors are represented by each case as illustrated in the data presented in Table 1.

Table 1. Switching modes along with the corresponding voltage vector of the voltage source converter

Conducting Modes	S_a	S_b	S_c	U_α	U_β
U_0	0	0	0	0	0
U_1	1	0	0	$2V_{dc}/3$	0
U_2	1	1	0	$V_{dc}/3$	$\sqrt{3}V_{dc}/3$
U_3	0	1	0	$-V_{dc}/3$	$\sqrt{3}V_{dc}/3$
U_4	0	1	1	$2V_{dc}/3$	0
U_5	0	0	1	$-V_{dc}/3$	$-\sqrt{3}V_{dc}/3$
U_6	1	0	1	$V_{dc}/3$	$-\sqrt{3}V_{dc}/3$
U_7	1	1	1	0	0

Depending on the mode of the switching vector (s_a,s_b,s_c) the stator voltage u_{dq} of the PMSM is calculated:

$$u_{dq}(k)= \frac{2\,A\,v_{dc}}{9} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (15)$$

$$A=\begin{bmatrix} \cos\phi_r & \sin\phi_r \\ -\sin\phi_r & \cos\phi_r \end{bmatrix} \quad (16)$$

5 Results and Discussion

The proposed technique MPC-SMC-MRAS is shown in Figure 3 (Appendix), where the speed is estimated based on the MRAS technique and the disturbance is removed. The role of the SMC technique allows approximating the speed to the reference speed, in addition to improving the reference current used in MPC.

Finally, the cost function based on the rated currents is used. In determining the best position for voltage vectors.

The results shown under various operating conditions with machine parameters are shown in Table 2.

Table 2. PMSM parameters

Parameter	Value
dq axis inductance [H]	0.0058
Flux induced by magnets [Wb]	0.1546
Number of poles	3
Rotor inertia [kg*m2]	0.00167
Viscous friction [N m]	0.000388
Stator resistance [Ω]	1.4
Sampling time [µs]	4
MRAS gains	kp=60, ki=3000000
SMC gains	k1=0.0176 ,k2=1

The motor current values become close to 2A, which is an expected response to the increased load. The increase in current is necessary to maintain the motor's speed at 100 RPM under the higher load condition. The control system shows flexibility to changes in load conditions. The model predictive

Figure 4 shows that at the start, the PMSM motor is running at a constant speed of 100 RPM. The load torque (TL) is relatively low at 0.5 Nm. The motor current is at 1A, indicating that the control system is maintaining the desired performance under this load condition. This stable current response suggests that the control algorithms are effectively regulating the motor operation. At t = 0.2 seconds, there is a sudden change in load torque from 0.5 Nm to 2 Nm. This change in load torque, particularly when it happens abruptly, can cause a transient response in the system control and model reference adaptive system give off an impression of being successful in answering burden disturbances. The sliding mode control might assume a part in keeping up with the system strength during transient states, like the unexpected change in load.

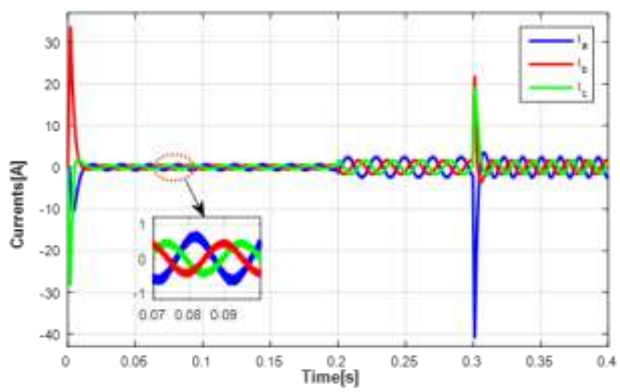

Fig. 4: Stator currents

Figure 5 gives significant bits of knowledge into the control system's performance, exhibiting its capacity to direct current and answer load changes while keeping a constant current i_d in accordance with commonplace PMSM control techniques. The convergence of quadratic current i_q and i_{qref} is a positive indication of the control system's capacity to successfully regulate current effectively. The expansion in i_q to 3A will be an immediate reaction to the expanded burden force, as most would consider normal.

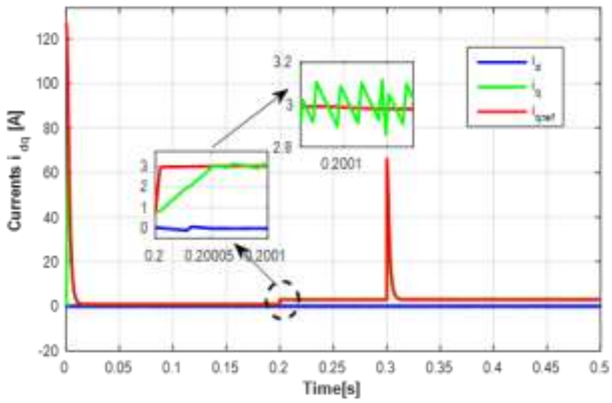

Fig. 5: Currents i_d ,i_q ,i_{qref}

The constant value of id at zero A indicates that the motor is operating in a state where there is no need for additional magnetizing current, which is consistent with typical PMSM control strategies.

In Figure 6, the speed error initially peaks at 100 RPM and gradually reduces to 0 RPM, indicating successful speed regulation under the initial load condition. When the load abruptly changes to 2 Nm, the speed error increases to 0.02, demonstrating a transient response to the load change. This small speed error shows that the control framework rapidly adjusts to the expanded burden, demonstrating effective speed control and stability.

Tweaking the control boundaries might additionally limit transient deviations, advancing overall performance.

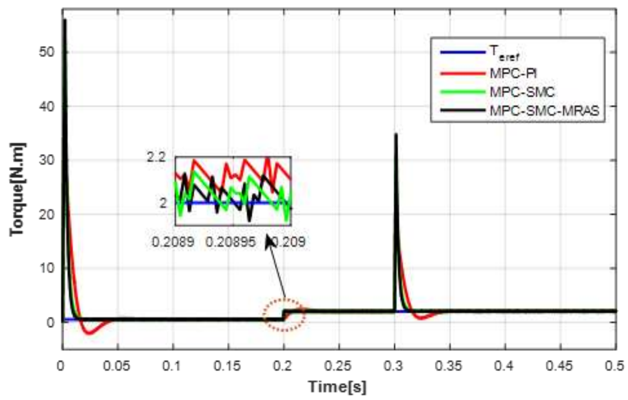

Fig. 6: Torque of PMSM

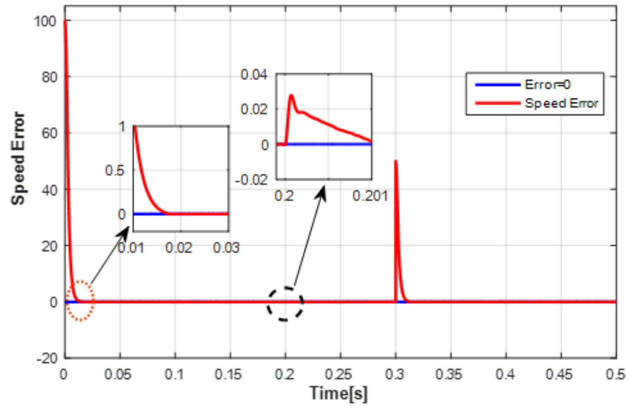

Fig. 7: Error of PMSM speed

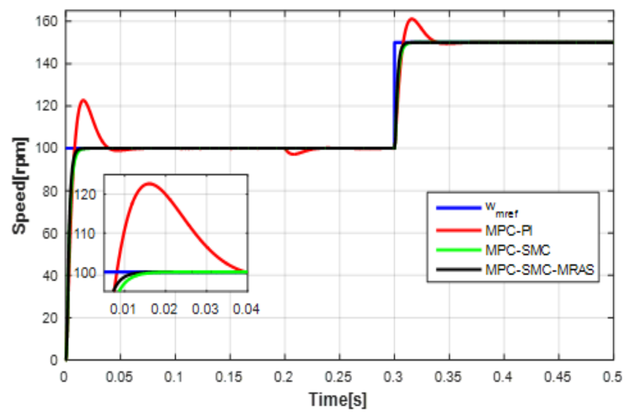

Fig. 8: Rotation speed of PMSM

In Figure 7, torques values for various control methods, incorporating PI with MPC, MPC with Sliding Mode Control (SMC), MPC with SMC, and Model Reference Adaptive System (MRAS), intently match the reference torque. This demonstrates the adequacy of these control techniques in tracking and keeping up with the ideal torque yield. The comparability between the actual torque and reference torque indicates well control execution for various strategies. Therefore, it indicates good adaptability of the control system to load disturbance and external disturbance and good torque control accuracy: These findings suggest the chosen control methods successfully maintained motor performance throughout the experiment.

Speed responses with various control techniques PI with MPC, MPC with SMC, MPC and MRAS in the respective presentation are shown in Figure 8. At first, speed holds at 100 RPM at a 0.5 Nm load. The speed reduces momentarily when the load instantly changes to 2 Nm at 0.2 s, then steady's out. At 0.3 s, speed surges to 150 RPM and stabilizes again. Clearly, these techniques are stable and adaptive to the load variations, which are much less stable comparing with the PI regulator. It follows that advanced control methods are essential for keeping speed as desired and for quickly adapting to changing loads.

6 Performance of the System

The basic experiences into the presentation and effectiveness of the proposed control techniques are given by Figure 9. The settling time, as an indicator of speed stability, is also an important metric to evaluate the control systems. The settling time for the PI regulator is substantially longer when contrasted with alternate techniques, which finds much slower reactions and probably less productivity. The observed speed fluctuations due to load changes are expected and reflect the system's adaptability to external disturbances.

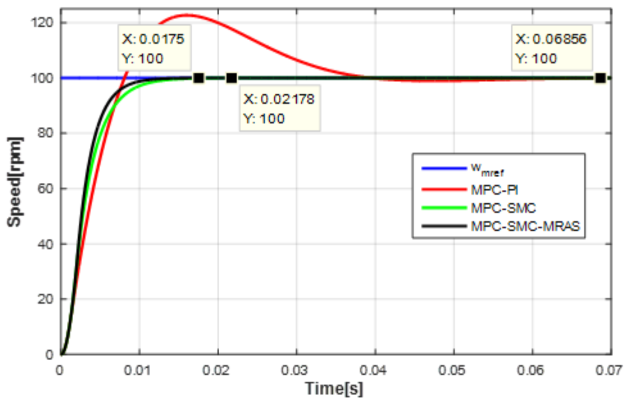

Fig. 9: Settling time of PMSM speed

The ability to recover and return to a stable speed signifies the robustness of these control techniques. Both the magnitude of the speed drop during load changes and the settling time are indicative of motor performance. Smaller speed drops and shorter settling times, as seen in the advanced control methods, imply better performance and faster response to load variations. This underscores the advantage of employing sophisticated control strategies over traditional ones like PI control in achieving more efficient and responsive motor operation.

Figure 10 shows that the speed drop is small, and the settling time is small in the MPC-SMC-MRAS technique at load 2 Nm at time 0.2 s

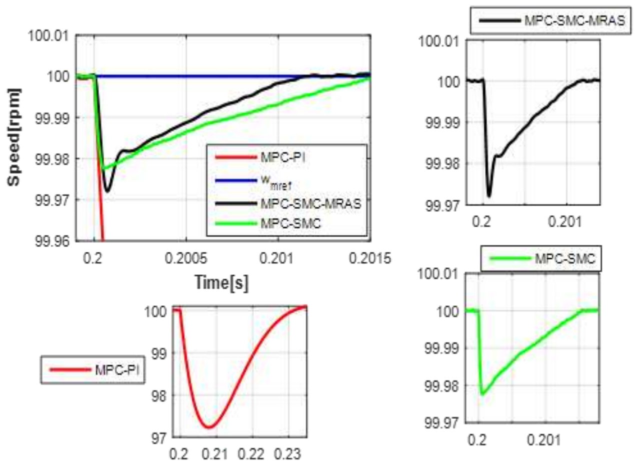

Fig. 10: speed drop of PMSM

The comparison results between specific control techniques for motor performance are shown in Table 3.

Table 3. Performance.

Dynamics	MPC-PI	MPC-SMC	MPC-SMC-MRAS
Settling time[s]	0.06856	0.02178	0.0175
Overshoot [rpm]	22.7	0.002	0.001
Steady state error [%]	0.05	0.01	0.01
Speed drop [rpm] with	2.77	0.023	0.028
settling time [s]	0.03	0.002	0.001
Adding T_L=2			

7 Conclusion

The introduced work shows a unique control system that joins Model Predictive Control (MPC) and Sliding Mode Control (SMC) while overriding the standard PI controller with SMC for current taking care of and assumption. Besides, the Model Reference Adaptive System (MRAS) is united to assuage speed aggravations. The MPC-SMC-MRAS model displays tremendous advantages over elective control plans. The key discoveries are as per the following: The proposed MPC-SMC-MRAS approach really lessens force-unsettling influences, guaranteeing exact control of engine force, and the blend of MPC, SMC, and MRAS prompts areas of strength for a responsive speed control system. The control system can rapidly adjust to changes in load, as shown by diminished settling times and limited speed drops. A similar examination uncovers that the MPC-SMC-MRAS model beats both MPC-SMC and MPC-PI setups as far as force and speed control, exhibiting its superior performance and robustness. Experimental validation will allow us to fine-tune the SMPC with MRAS for real-world conditions, and it can provide valuable data on its effectiveness in dynamic settings.

To resume MPC-SMC-MRAS can enhance precision, adaptability, and energy efficiency in sensor networks and power grids. It offers robust disturbance rejection and real-time adaptability, crucial for dynamic load management and stability. This technique supports fault tolerance and efficient power management, making it ideal for applications requiring reliable and adaptive control.

References:

[1] Ehsani, M., Gao, Y., Longo, S. & Ebrahimi, K. *Modern electric, hybrid electric, and fuel cell vehicles.* (CRC press, 2018), doi: M10.1201/9780429504884.

[2] Baader, U., Depenbrock, M., Gierse, G. "Direct self-control (DSC) of inverter-fed induction machine: a basis for speed control without speed measurement", *IEEE transactions on industry applications*, 28(3), pp. 581-588, 1992, doi: 10.1109/28.137442.

[3] Sriprang, S., Nahid-Mobarakeh, B., Takorabet, N., Thounthong, P., Pierfederici, S., Kumam, P., Mungporn, P. "Modeling of Flatness-Based Control with Disturbance Observer-Based Parameter Estimation for PMSM Drive." *WSEAS Transactions on Electronics*, 10(3), 19-27, 2019.

[4] Muthurajan, S., Loganathan, Rajaji, et Hemamalini, R. Rani. "Deep Reinforcement Learning Algorithm based PMSM Motor Control for Energy Management of Hybrid Electric Vehicles". *WSEAS Transactions on Power Systems*, vol. 18, p. 18-25, 2023, https://doi.org/10.37394/232016.2023.18.3.

[5] V. M. Venkateswara Rao, G. Chandra Sekhar, Y. P. Obulesh. "Artificial Neural Network and Adaptive Neuro Fuzzy Control of Direct Torque Control of Induction Motor for Speed and Torque Ripple Control." *WSEAS Transactions on Power Systems*, vol.13, pp.414-421, 2018.

[6] Dai, Bin, and Zuo Wang. "Disturbance observer-based sliding mode control using barrier function for output speed fluctuation constraints of PMSM." *IEEE Transactions on Energy Conversion*, vol. 39, no. 2, pp. 1192-1201, June 2024, 10.1109/TEC.2023.3349033.

[7] Yin, Z., Yan, G., Gao, F., Zhang, Y. "Sensorless model predictive current control of permanent magnet synchronous motor based on improved sliding mode observer", *In 2021 IEEE International Conference on Predictive Control of Electrical Drives and Power Electronics (PRECEDE),* Jinan, China, pp. 376-381, IEEE, 2021, doi: 10.1109/PRECEDE51386.2021.9680984.

[8] Kim, Y., Park, T., & Lee, J. M. "Integration of model predictive control and backstepping approach and its stability analysis", *IFAC-PapersOnLine*, 51(18), pp. 405-410, 2018, doi: 10.1016/j.ifacol.2018.09.334.

[9] Li, T., Sun, X., Lei, G., Yang, Z., Guo, Y., Zhu, J. "Finite-control-set model predictive control of permanent magnet synchronous motor drive systems—an overview", *IEEE/CAA Journal of Automatica Sinica*, *9*(12), 2087-2105, 2022, doi: 10.1109/JAS.2022.105851.

[10] Morawiec, M. "The adaptive backstepping control of permanent magnet synchronous motor supplied by current source inverter", *IEEE Transactions on Industrial Informatics*, 9(2), pp. 1047-1055, 2012, doi: 10.1109/TII.2012.2223478.

[11] Teng, Q. F., Li, G. F., Zhu, J. G., & Guo, Y. G. "Automatic Disturbances Rejection Control-Based Model Predictive Torque Control for Permanent Magnet Synchronous Motor with Three-Phase Four-Switch Inverter." *WSEAS Transactions on Systems and Control*, vol.11, pp.361-370, 2016.

[12] Salem, F., Awadallah, M. A., & Bayoumi, E. H "Model Predictive Control for Deadbeat Performance of Induction Motor Drives." *WSEAS Transactions on Circuits and Systems*, vol.14, pp.303-311, 2015.

[13] Karamanakos, P., Liegmann, E., Geyer, T., Kennel, R. "Model predictive control of power electronic systems: Methods, results, and challenges", *IEEE Open Journal of Industry Applications*, 1, pp. 95-114, 2020, doi: 10.1109/OJIA.2020.3020184.

[14] Swief, A., El-Zawawi, A., & El-Habrouk, M. "A survey of model predictive control development in automotive industries", *In 2019 International Conference on Applied Automation and Industrial Diagnostics (ICAAID)*, Elazig, Turkey, pp. 1-7, IEEE, 2019, doi: 10.1109/ICAAID.2019.8934974.

[15] Rodriguez, J., Garcia, C., Mora, A., Flores-Bahamonde, F., Acuna, P., Novak, M., Aguilera, R. P. "Latest advances of model predictive control in electrical drives—Part I: Basic concepts and advanced strategies", *IEEE Transactions on Power Electronics,* 37(4), 3927-3942, 2021, doi: 10.1109/TPEL.2021.3121532.

[16] Djouadi, H., Ouari, K., Belkhier, Y., Lehouche, H., Bajaj, M., & Blazek, V. "Improved robust model predictive control for PMSM using backstepping control and incorporating integral action with experimental validation." *Results in Engineering,* 23 (2024): 102416, doi: 10.1016/j.rineng.2024.102416.

[17] Xiao, F., Chen, Z., Chen, Y., & Liu, H."A finite control set model predictive direct speed controller for PMSM application with improved parameter robustness." *International Journal of Electrical Power & Energy Systems,* 143 (2022): 108509, doi: 10.1016/j.ijepes.2022.108509.

[18] Huangfu, L., Cen, C., & Zhang, T. "Improved model predictive control of permanent magnet synchronous motor based on lumped disturbance compensation", 2023, Research Square, doi: 10.21203/rs.3.rs-3678797/v1.

[19] Bao, G., Qi, W., He, T. "Direct torque control of PMSM with modified finite set model predictive control", Energies, 13(1), 234, 2020, doi: 10.3390/en13010234.

[20] Aboelhassan, A., El Sayed, W., Hebala, A., Galea, M., Bozhko, S. "Fault tolerant control strategy based on model predictive control and unscented Kalman filter for permanent magnet synchronous motor", *In 2021 IEEE 16th Conference on Industrial Electronics and Applications (ICIEA),* Chengdu, China, pp. 153-159, IEEE, 2021, doi: 10.1109/ICIEA51954.2021.9516257.

[21] Younesi, A., Tohidi, S., Feyzi, M. R., Baradarannia, M. "An improved nonlinear model predictive direct speed control of permanent magnet synchronous motors", *International Transactions on Electrical Energy Systems,* 28(5), p. e2535, 2018, doi:10.1002/etep.2535.

[22] Cao, B., Grainger, B. M., Wang, X., Zou, Y., Reed, G. F., & Mao, Z. H. "Direct torque model predictive control of a five-phase permanent magnet synchronous motor." *IEEE Transactions on Power Electronics,* 36.2 (2020): 2346-2360, doi: 10.1109/TPEL.2020.3011312.

[23] Bouguenna, I. F., Tahour, A., Kennel, R., Abdelrahem, M. "Multiple-vector model predictive control with fuzzy logic for PMSM electric drive systems", *Energies,* 14(6), 1727, 2021, doi: 10.3390/en14061727

[24] Wei, Y., Wei, Y., Gao, Y., Qi, H., Guo, X., Li, M., Zhang, D. "A variable prediction horizon self-tuning method for nonlinear model predictive speed control on PMSM rotor position system", *IEEE Access,* 9, pp. 78812-78822, 2021, doi: 10.1109/ACCESS.2021.3084321.

[25] Li, Z., Wang, F., Ke, D., Li, J., Zhang, W. "Robust continuous model predictive speed and current control for PMSM with adaptive integral sliding-mode approach", *IEEE Transactions on Power Electronics,* 36(12), pp. 14398-14408, 2021, doi: 10.1109/TPEL.2021.3086636.

[26] Karboua, D., Chouiha, Y., Douara, B. O., Bouguenna, I. F., Benkaihoul, S., & Toual, B. "Advanced Dual-Loop Control Architecture for Superior PMSM Performance Utilizing Finite-Control-Set Model Predictive Control and Exponential Reaching Law Sliding Mode Control." *ITEGAM-JETIA*, *10*(49), 71-79, 2024, doi:10.5935/jetia.v10i49.1221.

[27] Pilla, R., Gorripotu, T. S., Azar, A. T. "Tuning of extended Kalman filter using grey wolf optimisation for speed control of permanent magnet synchronous motor drive", *International Journal of Automation and Control*, 15(4-5), pp. 563-584, 2021, doi: 10.1504/IJAAC.2021.116423.

[28] Wei, C., Yankun, C., Hongfeng, L., & Zhanfeng, S. (2012, June). "Sensorless control of permanent magnet synchronous motor based on sliding mode observer". *In Proceedings of The 7th International Power Electronics and Motion Control Conference,* Harbin (Vol. 4, pp. 2582-2586). IEEE, doi: 10.1109/IPEMC.2012.6259266.

[29] Mansour, M., Hadj Saıd, S., Bendoukha, S., Berrayana, W., Mansouri, M. & Mimouni, M. "High-gain observer-based sensorless control of a flywheel energy storage system for integration with a grid-connected variable-speed wind generator. *Soft Computing*. 24 pp. 10585-10596 312 (2020), doi: 10.1007/s00500-019-04564-5.

[30] Ge, Y., Yang, L., & Ma, X. "Adaptive sliding mode control based on a combined state/disturbance observer for the disturbance

rejection control of PMSM", *Electrical engineering*, 102, pp. 1863-1879, 2020, doi: 10.1007/s00202-020-00999-4.

[31] Hezzi, A., Abdelkrim, M. & Elghali, S. "Sensorless backstepping drive for a five-phase pmsm based on unknown input observer ". *2020 20th International Conference on Sciences and Techniques Of Automatic Control and Computer Engineering (STA)*, Monastir, Tunisia. pp. 125-130 (2020), doi: 10.1109/STA50679.2020.9329327.

[32] Wang, S., Yang, K. & Chen, K. "An improved position-sensorless control method at low speed for PMSM based on high-frequency signal injection into a rotating reference frame ". IEEE Access. 7 pp. 86510-86521(2019), doi: 10.1109/ACCESS.2019.2925214.

[33] Badini, S. & Verma, V. "MRAS-based speed and parameter estimation for a vector-controlled PMSM drive." *Electrica*. 20, 28-40 (2020), doi: 10.5152/electrica.2020.19039.

[34] Zhang, W., Yang, Z., Zhai, L. & Wang, J. "Speed sensorless control of hybrid excitation axial field flux-switching permanent-magnet machine based on model reference adaptive system." *IEEE Access*. 8 pp. 22013-22024 (2020), doi: 10.1109/ACCESS.2020.2967098.

[35] Karboua, D., Toual, B., Kouzou, A., Douara, B., Mebkhouta, T. & Bendenidina, A. "High-order supper-twisting based terminal sliding mode control applied on three phases permanent synchronous machine. *Periodica Polytechnica Electrical Engineering and Computer Science*. 67, 40-50 (2023), doi: 10.3311/PPee.21026.

[36] Bouguenna, I., Azaiz, A., Tahour, A. & Larbaoui, A. Robust neuro-fuzzy sliding mode control with extended state observer for an electric drive system. *Energy*. 169 pp. 1054-1063 (2019), doi: 10.1016/j.energy.2018.12.101.

[37] Zhang, S., Shen, A., Luo, X., Tang, Q. & Li, Z. "Multi-sliding mode current disturbance suppression scheme based model reference adaptive system for sensorless control of permanent magnet synchronous motor." *ISA Transactions*. 137 pp. 615-628 (2023), doi: 10.1016/j.isatra.2023.01.024.

[38] Meryem, B., Abdelhamid, B., Abdelkarim, A. & Eddine, Z. "Real-time control of PMSM motor drive based MRAS-STC technique." *2022 19th International Multi-Conference On Systems, Signals Devices (SSD)*, Sétif, Algeria. pp. 1658-1663 (2022), doi: 10.1109/SSD54932.2022.9955913.

[39] Moujahed, M., Touaiti, B., Azza, H. B., Jemli, M., Boussak, M. "Fault Tolerant Power Converter Topologies for Sensor-less Speed Control of PMSM Drives", *Periodica Polytechnica Electrical Engineering and Computer Science*, 63(3), pp. 227-234, 2019, doi:10.3311/PPee.14048.

[40] Yue, Y., Geng, Y., Wang, W. "Continuous Nonsingular Fast Terminal Sliding Mode Control for Speed Tracking of PMSM Based on Finite Time Disturbance Observer", *Processes*, 10(7), p. 1407, 2022, doi:10.3390/pr10071407.

[41] Khadar, S., Abu-Rub, H., & Kouzou, A. "Sensorless Sliding Mode Control of Open-End Dual-Stator Induction Motor using Extended Kalman Filter", *In 2021 18th International Multi-Conference on Systems, Signals & Devices (SSD)*, Monastir, Tunisia, pp. 1136-1141, IEEE, 2021, doi: 10.1109/SSD52085.2021.9429471.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

-Ibrahim Farouk Bouguenna, Said Benkaihoul conceived and developed the primary concept of the study, contributed to the theoretical framework and literature review, conducted simulations

-Mohammed Benmadani Debbat, Abdelghani Zabel, and Tahour Ahmed assisted in refining the results and their interpretation, supported manuscript preparation and formatting.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.

Ibrahim Farouk Bouguenna,
Said Benkaihoul, Mohammed Benmadani Debbat,
Abdelghani Zabel, Tahour Ahmed

APPENDIX

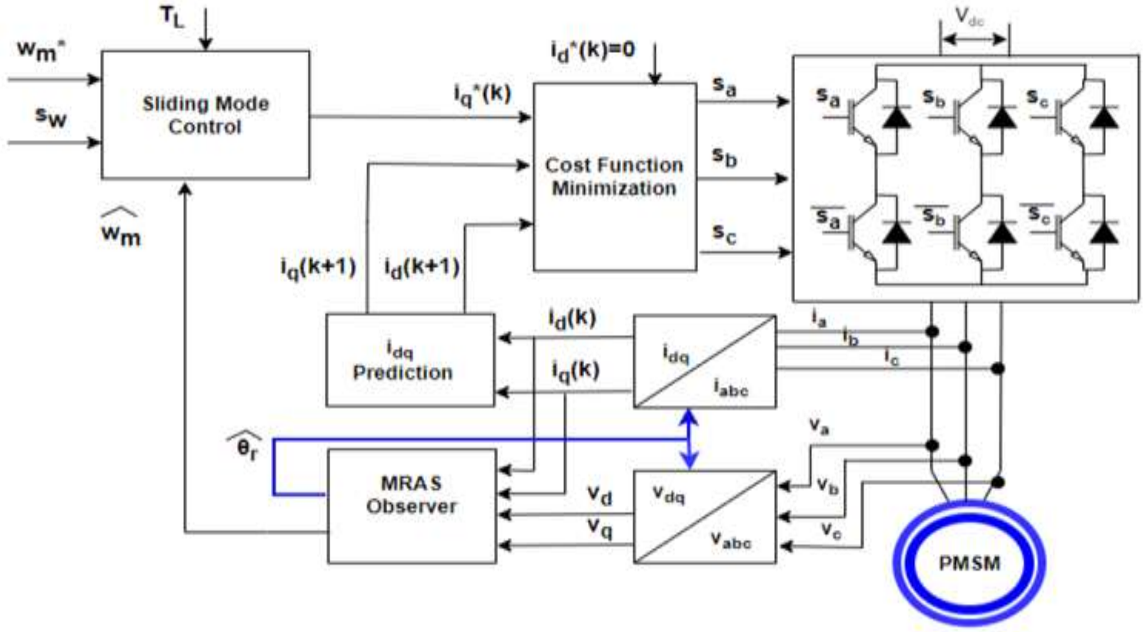

Fig. 3: PMSM diagram