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ENHANCING PERFORMANCE OF PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVES THROUGH HYBRID FEEDBACK LINEARIZATION AND SLIDING MODE CONTROL

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ABSTRACT

This paper proposes a novel hybrid control strategy that integrates Feedback Linearization Control (FBLC) with Sliding Mode Control (SMC) to significantly enhance the performance of Permanent Magnet Synchronous Motor (PMSM) drives. The proposed control strategy leverages the strengths of both FBLC and SMC to address the inherent challenges associated with PMSM control in demanding industrial applications. The FBLC component of the hybrid controller effectively linearizes the nonlinear dynamics of PMSMs. By transforming the nonlinear system into an equivalent linear system, FBLC facilitates precise trajectory tracking and improves transient response, thereby ensuring high control accuracy. This linearization process simplifies the control design and enables the implementation of advanced linear control techniques. On the other hand, the SMC component ensures robustness and reliability of the PMSM drive system. SMC is known for its inherent robustness against parameter variations, uncertainties, and external disturbances. By incorporating SMC into the hybrid controller, the system maintains stable and reliable operation even in the presence of these adverse conditions. The SMC component enhances disturbance rejection capabilities, providing a robust control solution that significantly improves the overall system performance. The integration of FBLC and SMC into a unified control architecture results in a synergistic improvement in PMSM drive performance. The hybrid FBLC-SMC controller combines the precise tracking capabilities of FBLC with the robustness of SMC, leading to superior tracking accuracy, effective disturbance rejection, and enhanced overall robustness compared to traditional control methods. Extensive simulation studies are conducted to validate the effectiveness of the proposed hybrid control strategy. The simulation results demonstrate the ability of the FBLC-SMC controller to achieve excellent performance metrics, including improved tracking accuracy, faster transient response, and robust disturbance rejection. The hybrid control strategy is shown to be a promising solution for industrial applications requiring high performance and reliability in PMSM control.

I. INTRODUCTION

Electric motors play a pivotal role in a wide array of industries, converting electrical energy into mechanical power that drives applications ranging from electric vehicles to industrial machinery. Among the various types of electric motors, Permanent Magnet Synchronous Motors (PMSMs) are particularly renowned for their high efficiency and precision. These motors employ permanent magnets in the rotor to ensure synchronized magnetic fields with the stator, a configuration that significantly enhances their performance characteristics. However, despite their advantages, PMSMs are inherently complex due to their nonlinear, coupled, and multivariable nature. This complexity necessitates the development of advanced control strategies to achieve optimal performance [1-3]. Traditional control methods, such as Field-Oriented Control (FOC), have been widely used to manage PMSMs. FOC operates by decoupling the flux and torque components, thereby optimizing motor performance. While effective in many scenarios, FOC can struggle with maintaining robustness in the face of parameter variations and external disturbances [4],[5]. To address these limitations, researchers have increasingly turned to advanced control techniques that incorporate nonlinear control, optimization, and robustness methodologies. These techniques include feedback linearization, sliding mode control (SMC), backstepping control, adaptive control, and various intelligent techniques. The primary aim of these methods is to enhance the overall performance of PMSMs by effectively managing their nonlinear dynamics and mitigating uncertainties [6],[7]. Feedback Linearization Control (FBLC) is an advanced control method that simplifies control design by transforming a system's nonlinear dynamics into a linear system. This transformation enables the use of linear control techniques, which are well-established and generally easier to implement than nonlinear approaches. As a result, FBLC improves response times, precision, and disturbance rejection, benefiting from the advantages of linear control methods for more predictable and efficient system behavior. However, FBLC relies heavily on having an accurate mathematical model of the system, which can be computationally complex to obtain and maintain. In the context of PMSMs, FBLC's reliance on precise modeling can be particularly challenging due to the motors' inherent complexity and sensitivity to parameter variations. Any inaccuracies in the model can lead to suboptimal performance or instability, as the linearization process may not fully capture the motor's nonlinearities. Additionally, the computational demands for real-time state estimation and parameter tuning required by FBLC can be significant, potentially impacting the system's overall efficiency and performance. Despite these challenges, when accurately implemented, FBLC can greatly enhance the performance of complex nonlinear systems by providing a robust and precise control framework. [8],[9]. Sliding Mode Control (SMC) is renowned for its robustness against parameter variations and external disturbances, making it a highly effective control strategy for systems like PMSMs. SMC achieves this robustness by forcing the system's trajectory to adhere to a predefined sliding surface, ensuring stability and reliable operation even under varying conditions. However, SMC is not without its drawbacks. A significant issue is chattering, which involves high-frequency oscillations in the control input as it switches rapidly to keep the system on the sliding surface. This chattering can lead to mechanical wear, increased energy consumption, and reduced system efficiency. Additionally, designing an effective SMC system requires meticulous tuning of parameters to balance performance and robustness, which can be complex and time-consuming. Despite these challenges, SMC remains a valuable control strategy due to its ability to maintain stable operation under uncertain conditions [10],[11]. In this paper, we propose a hybrid control strategy that integrates Feedback Linearization Control (FBLC) with Sliding Mode Control (SMC) to enhance the performance of PMSM drives. The hybrid approach is designed to combine the advantages of both control techniques, leveraging FBLC's precision and improved response times alongside SMC's robustness and effective disturbance rejection. This integration aims to achieve superior control accuracy, increased efficiency, and enhanced stability of PMSM drives, effectively addressing and mitigating the limitations associated with each individual technique. Through this detailed exploration, we aim to demonstrate that the proposed hybrid FBLC-SMC control strategy offers a promising solution for enhancing the performance and reliability of PMSM drives in demanding industrial applications. The remainder of this paper is structured as follows: Section 2 provides a detailed exploration of the modeling of PMSM dynamics, offering a thorough understanding of the system's behavior. Section 3 focuses on designing the FBLC-SMC control strategy for the PMSM, detailing the development and integration of the hybrid control approach. Section 4 presents extensive simulation studies designed to validate the effectiveness of the proposed hybrid control strategy, accompanied by a comprehensive discussion of the findings. Finally, Section 5 concludes the paper by summarizing the key contributions and insights gained from the research.

II. FORMULATING A NONLINEAR MODEL OF THE PMSM SYSTEM

The d-q rotor reference frame simplifies PMSM equations, improving computational efficiency and control system design by maintaining steady-state variables. This model assumes a cage-free rotor, sinusoidal back-EMF, and minimal saturation, eddy currents, and hysteresis losses. Due to the inherent nonlinearity of PMSMs, a direct nonlinear modeling approach is favored for effectively handling system disturbances without requiring decoupling or linearization, ensuring comprehensive and accurate representation [12],[13].

$$\begin{cases} \frac{d}{dt}x(t) = f(x(t)\,, u(t)\,, t) + g(t) * u(t) \\ y(t) = h(x(t)) \end{cases} \tag{1}$$

Where $x(t)$ are the state variables, $f(x(t)\,, u(t)\,, t)$ is the nonlinear function, $u(t)$ is the system input, and y(t) is the system output.

The inputs, state space variables and the output for the PMSM model is designed as follows:

$$\begin{cases} u(t) = [v_d \quad v_q]^T \\ x(t) = [i_d \quad i_q \quad \omega_e]^T \\ y(t) = h(x) = \omega_e \end{cases} \tag{2}$$

The terms of the nonlinear mentioned above for the PMSM model is identified as follow:

$$f(x(t), u(t), t) = \begin{bmatrix} -\frac{R_s}{L_d}.i_d + \frac{L_q}{L_d}.i_q.\omega_e \\ -\frac{R_s}{L_q}.i_q - \frac{L_d}{L_q}.i_d.\omega_e - \frac{\psi_f}{L_q}.\omega_e \\ -\frac{F}{j}.\omega_e + \frac{3.p^2}{2}.\frac{L_d - L_q}{j}.i_d.i_q + \frac{3.p^2}{2}.\frac{\psi_f}{j} * i_q - \frac{p}{j}.T_l \end{bmatrix} \tag{3}$$

And

$$g(t) = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \quad (4)$$

Where: i_d, i_q are d-q axis equivalent stator currents; v_d, v_q are d-q axis equivalent stator voltages; ω_e is rotor speed; p is number of pole pairs; R_s is per phase stator resistance; L_d, L_q are d-q axis equivalent stator inductance ; Te, T_l are electromagnetic and load torques ; J is moment of inertia of the rotor ; F is friction constant of the rotor and ψ_f is rotor magnetic flux linking the stator.

III. DESIGNING THE FBLC-SMC FOR THE PMSM

In control systems engineering, the feedback linearization algorithm transforms nonlinear systems into linear ones through state manipulation and feedback, avoiding approximation [14]. When applied to a PMSM system, feedback linearization aims to:
1) Eliminate nonlinearities to establish a closed-loop linear system;
2) Simplify system design post-linearization;
3) Use linear control strategies for stability, desired performance, and disturbance rejection.

This is achieved through input-output linearization, ensuring complete linearization between system outputs and control inputs:

$$\begin{cases} y_1 = i_d \\ y_2 = \Omega \end{cases} \quad (5)$$

The trajectories for these two outputs must be strictly adhered to. Implementing a maximum torque strategy necessitates setting $i_d^* = 0$, while the speed Ω must track its specified reference pat Ω^*. This reference path for Ω^* can vary depending on the application requirements.

III.1 FOR THE FIRST OUTPUT i_d:

$$y_1 = i_d = h_1(x), \nabla h_1(x) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad (6)$$

Where: $\omega_r = p\Omega$ .To find the derivative of the first output, we proceed as follows:

$$\begin{cases} y_1 = i_d = h_1(x) \\ \dot{y}_1 = L_f h_1(x) = -\frac{R_s}{L_d}.i_d + \frac{L_q}{L_d}.p.\Omega.i_d + \frac{1}{L_d}.u_d \end{cases} \quad (7)$$

III.2 FOR THE SECOND OUTPUT Ω:

$$y_2 = \Omega = h_2(x), \nabla h_2(x) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (8)$$

Since the input has not yet been introduced, we proceed to calculate the second derivative of the second output as follows:

$$\begin{cases} y_2 = \Omega = h_2(x) \\ \dot{y}_2 = \frac{3.p}{2.J}(\psi_f.L_q + (L_d - L_q).i_d.i_q) - \frac{1}{J}T_r - \frac{F}{J}.\Omega \\ \ddot{y}_2 = K_t(L_d - L_q).i_d.f_1(x) + K_t(\psi_f + (L_d - L_q).i_d)f_2(x) \\ -\left(\frac{1}{J}T_r + \frac{F}{J}\right)f_3(x) + \frac{K_t}{L_q}(L_d - L_q).i_d.u_q \\ +\frac{K_t}{L_q}(\psi_f + (L_d - L_q).i_d).u_d \end{cases} \quad (9)$$

where: $K_t = \frac{3.p}{2.J}$

Since the relative degree is $r_1 + r_2 = 3 = n$ (order the system), we have:

$$[\dot{y}_1 \quad \ddot{y}_2]^T = a(x) + b(x).u \quad (10)$$

Therefore, the nonlinear terms are cancelled out by choosing a transformation:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = b^{-1}(x)\left(\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} - a(x)\right) \quad (11)$$

Where the $b(x)$ matrix is smooth. After canceling the non-linearity of the PMSM dynamic system:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{e}_d + K_d.e_d \\ \ddot{e}_\omega + K_{\omega 1}.e_\omega + K_{\omega 2}.e_\omega \end{bmatrix} \quad (12)$$

where:

$$\begin{cases} e_1 = i^*_d - i_d \\ e_\omega = \Omega^* - \omega \end{cases} \quad (13)$$

To enhance FBLC, SMC is integrated into its control law. SMC establishes a surface to ensure stability and performance by guiding the system's trajectory towards and along this surface. It operates in two phases: driving the system to the sliding surface and maintaining motion on it, moving towards equilibrium in finite time. Implementing SMC involves three steps: selecting the sliding surface, defining sliding conditions, and computing the SMC law [15],[16].

$$S(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) \quad (14)$$

In SMC, λ is a positive parameter chosen by the designer to control the error dynamics, while n denotes the system's order. $S(x,t)$ is the sliding surface, and $e(t)$ is the tracking error. The system's trajectory is directed towards the origin and reaches it asymptotically, governed by the sliding condition in the following equation [17]:

$$\frac{1}{2}\frac{d}{dt}S^2 \leq \eta|S| \quad (15)$$

Where $\eta > 0$

After establishing the sliding surface and meeting the sliding condition, the control law is determined in two phases. First, the sliding phase keeps the system on the sliding surface by designing an equivalent term where $S(x,t) = 0$ and $\dot{S}(x,t) = 0$. Next, the approach phase ensures the sliding condition by formulating a switching law where $S(x,t) \neq 0$ and $S(x,t) = 0$. The specific design of the SMC control law unfolds as follows [18]:

$$u = u_{eq} + u_s \tag{16}$$

Within this context, the tracking errors for speed and direct current can be expressed using Equation 13. Here, the switching approach based on SMC is introduced to enhance feedback linearization control (FBLC), replacing the linear dynamic of Equation 12 with a switching term as follows:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} -K_1 tanh(S) \\ -K_2 tanh(S) \end{bmatrix} \tag{17}$$

Where S is sliding surface of SMC and K_1 , K_2, are the gains used to regulate the SMC-FBLC.

IV. SIMULATION, RESULTS AND DISCUSSION

The efficacy of the hybrid control approach integrating Sliding Mode Control (SMC) and Feedback Linearization Control (FBLC) for a Permanent Magnet Synchronous Motor (PMSM) was thoroughly demonstrated through a comprehensive simulation model. This model was meticulously implemented using Matlab/Simulink, a powerful tool for modeling, simulating, and analyzing dynamic systems. The simulation setup included detailed representations of both the control strategies and the PMSM dynamics, ensuring an accurate assessment of the hybrid approach's performance. The simulation model, as illustrated in Figure 1, showcases the integration process of SMC and FBLC. It highlights the interaction between these two control methodologies and the PMSM, capturing the intricate dynamics and control responses. The model was designed to test various operating conditions and disturbances, providing a robust validation of the hybrid control strategy's capabilities. In addition to the simulation framework, the study specifies the detailed parameters of the PMSM used in the simulations. These parameters, outlined in Table 1. The detailed simulation study involved extensive testing under different scenarios to evaluate the hybrid control approach's performance in terms of response time, accuracy, disturbance rejection, and overall stability. The comprehensive results demonstrated that the SMC-FBLC hybrid control strategy significantly enhances the performance of PMSM drives, addressing the shortcomings of using either control method alone.

Table 1: Parameters of the PMSM drive.

PMSM's parameters		
R_s=0.6 Ω	L_d =1.4 × 10^{-3} H	L_q=2.8 × 10^{-3} H
F =1.4 × 10^{-3} $M.m.s^{-1}$	J =1.1 × 10^{-3} kg.m2	ψ_f=12× 10^{-2} Wb
v_{dc} = 100V		p=4

Source: Authors, (2024).

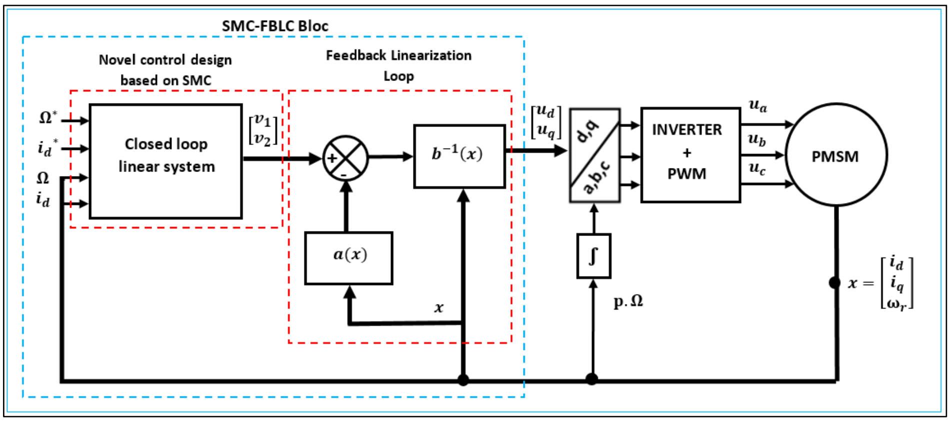

Figure 1: Scheme SMC-FBLC for the PMSM drive.
Source: Authors, (2024).

In the simulation study, the performance of the hybrid control approach integrating Sliding Mode Control and Feedback Linearization Control (SMC-FBLC) for a PMSM was rigorously compared with the classical Feedback Linearization Control (C-FBLC) under various operational scenarios. One notable scenario included a speed reversal from 200 rad/s to -200 rad/s (see Figure 2), which is a challenging test case due to the significant change in motor speed and direction. During the speed reversal test, the SMC-FBLC demonstrated superior performance compared to the C-FBLC. The hybrid control approach exhibited a faster rise time, meaning it was able to achieve the desired speed change more quickly and efficiently. This quick response is crucial in applications where rapid speed adjustments are necessary for optimal performance. Furthermore, the SMC-FBLC maintained a lower steady-state error throughout the simulation. Steady-state error measures the difference between the desired and actual motor speeds after the system has settled. A lower steady-state error indicates that the hybrid control strategy provides more precise control, maintaining the motor speed closer to the target value with minimal deviation.

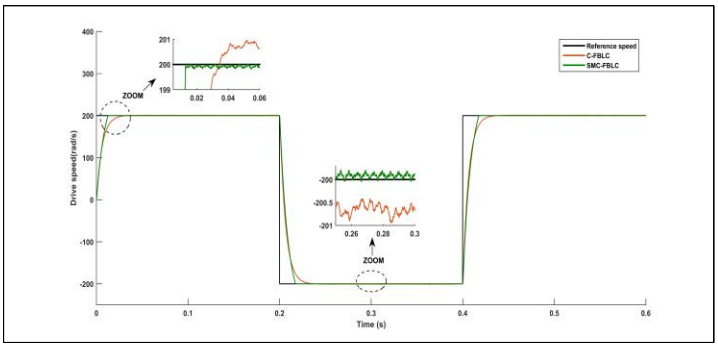

Figure 2: PMSM speed performance during the speed variation.
Source: Authors, (2024).

SMC-FBLC significantly reduces torque ripple and minimizes overshoot and undershoot during speed transitions (Figure 3), demonstrating robustness in dynamic response. In particular, the torque ripple reduction results in smoother operation, which is crucial for applications requiring precision and stability. The minimized overshoot and undershoot during speed transitions indicate that the system quickly and accurately reaches the desired speed without excessive deviations, enhancing performance and reliability.

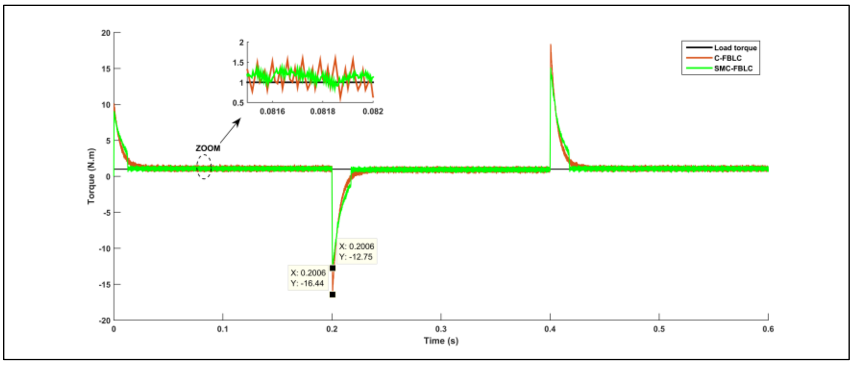

Figure 3: PMSM electromagnetic torque performance during the speed variation.
Source: Authors, (2024).

Additionally, the stator currents (i_{abc}) under SMC-FBLC control exhibit smoother and more stable behavior compared to C-FBLC (Figure 4 and 5). This smoother current response reduces mechanical stress on the motor components, leading to longer lifespan and reduced maintenance requirements. The direct-quadrature axis currents (i_{dq}) also show improved stability and reduced fluctuations under SMC-FBLC control (Figures 6). These findings highlight SMC-FBLC's superior effectiveness and reliability in controlling PMSMs, making it a preferable choice for applications demanding high precision and robust performance.

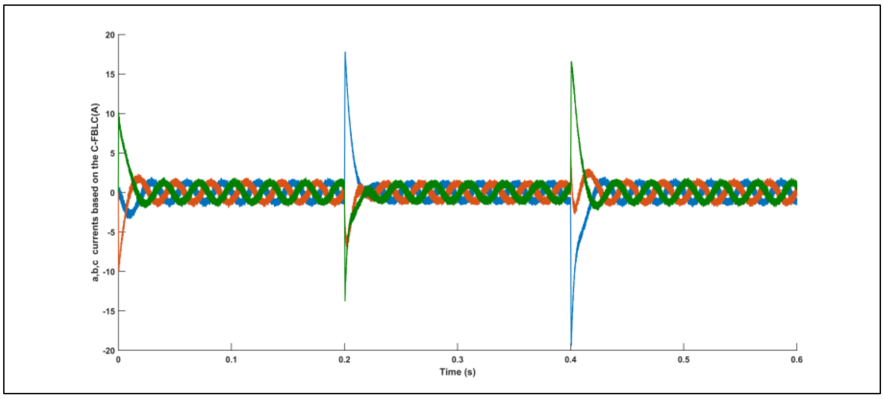

Figure 4: PMSM stator currents performance based on the C-FBLC during the speed variation.
Source: Authors, (2024).

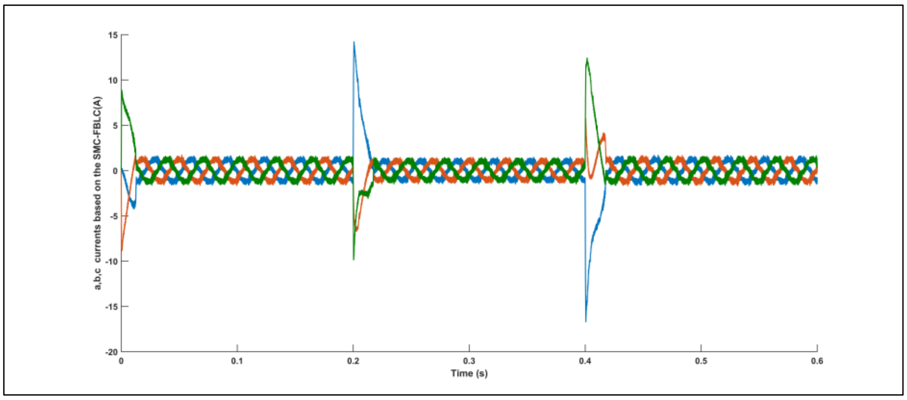

Figure 5: PMSM stator currents performance based on the SMC-FBLC during the speed variation.
Source: Authors, (2024).

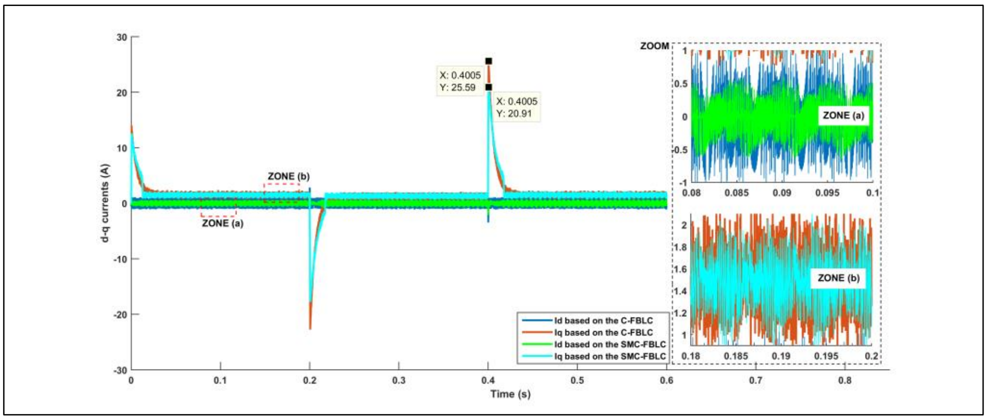

Figure 6: PMSM d-q currents performance during the speed variation.
Source: Authors, (2024).

In a test scenario with varying load torque, ranging from 1 N·m to 5 N·m, the robustness of the SMC-FBLC control design was thoroughly evaluated. Figure 7 illustrates that the SMC-FBLC maintained exceptional speed accuracy with minimal steady-state error, successfully achieving and sustaining the desired speeds despite the presence of external disturbances. Throughout the range of varying load torques, the control system demonstrated remarkable precision in speed regulation. The SMC-FBLC control exhibited quick and stable responses to sudden changes in load torque, effectively minimizing any transient deviations and ensuring consistent performance. Compared to traditional control technique, the SMC-FBLC displayed improved overall speed characteristics, including faster settling times and reduced overshoot, contributing to a more stable and reliable control performance. The system's ability to adapt seamlessly to dynamic variations in load torque underscores its efficiency in managing such conditions without compromising stability or accuracy.

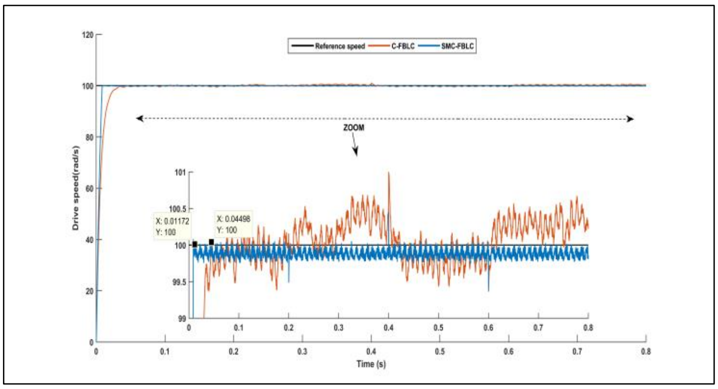

Figure 7: PMSM speed performance during applying load torque.
Source: Authors, (2024).

Under the combined SMC and FBLC techniques, the torque response of the PMSM exhibited significant enhancement, as illustrated in Figure 8. The most notable improvement was the substantial reduction in torque ripple. Torque ripple is a critical factor in motor performance, as excessive ripple can lead to undesirable vibrations and noise, which, in turn, cause mechanical stress on the motor components. By mitigating torque ripple, the SMC-FBLC control approach ensures smoother motor operation, which is crucial for applications requiring high precision and reliability. This reduction in mechanical stress not only extends the operational life of the motor but also enhances its overall performance and efficiency. Consequently, the improved torque response and reduced ripple contribute to the robustness and reliability of PMSM systems in various industrial applications, ultimately leading to better system stability and reduced maintenance costs. The effectiveness of the SMC-FBLC hybrid control strategy in achieving these outcomes underscores its potential as a superior alternative to traditional control methods, paving the way for its adoption in advanced motor control applications.

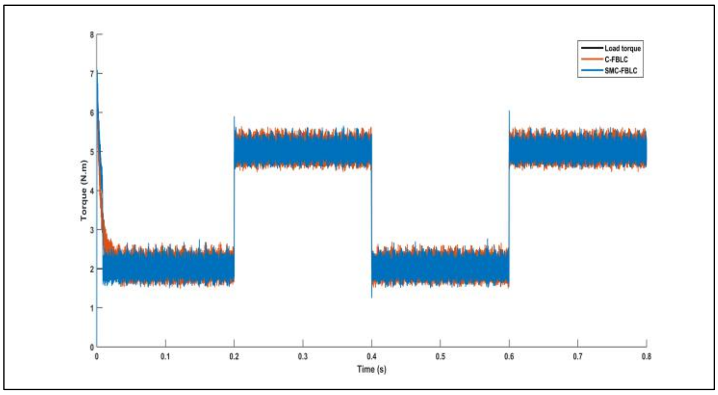

Figure 8: PMSM electromagnetic torque performance during applying load torque.
Source: Authors, (2024).

The hybrid control design combining Sliding Mode Control and Feedback Linearization Control (SMC-FBLC) significantly outperformed the classical Feedback Linearization Control (C-FBLC) in terms of current regulation. The results, illustrated in Figures 9, 10, and 11, show that the SMC-FBLC approach managed to maintain both stator currents (i_{abc}) and direct-quadrature axis currents (i_{dq}) with minimal deviations from their desired values. Specifically, the stator currents under SMC-FBLC experienced less overshoot and undershoot compared to C-FBLC.

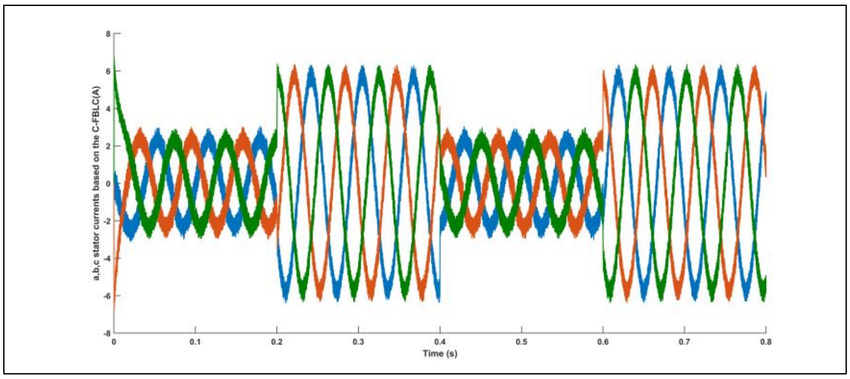

Figure 9: PMSM stator currents performance based on the C-FBLC during applying load torque.
Source: Authors, (2024).

This improved regulation under SMC-FBLC suggests that the hybrid method is more adept at handling transient responses. It ensures the currents remain within tighter bounds during dynamic changes, leading to a more stable system. Additionally, this precise control translates to enhanced power efficiency, as the system can more effectively manage energy consumption and reduce losses associated with current fluctuations. The stability provided by SMC-FBLC is particularly beneficial in applications requiring high precision and reliability, as it minimizes the effects of disturbances and uncertainties in the system. The ability to reduce transient responses further highlights the robustness of the hybrid control strategy, making it a valuable advancement over traditional control methods.

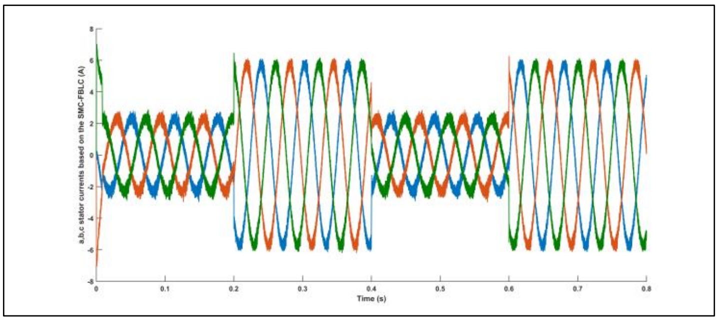

Figure 10: PMSM stator currents performance based on the SMC-FBLC during applying load torque.
Source: Authors, (2024).

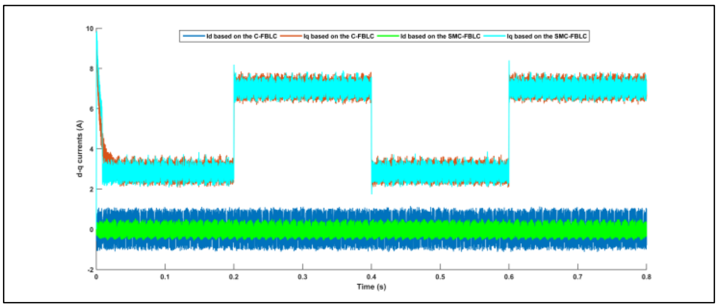

Figure 11: PMSM d-q currents performance during applying load torque.
Source: Authors, (2024).

In the last scenario, the robustness of the SMC-FBLC control strategy was evaluated by introducing uncertainties of -10%, -25%, 10%, and 25% (see Figure 12). The introduction of these uncertainties, which represent deviations from the nominal parameters of the system, simulates real-world scenarios where system parameters are not perfectly known or constant. Observations revealed only minor changes in rise time and slight variations in steady-state speed error, indicating the strategy's robust performance. These findings emphasize the stability and reliability of SMC-FBLC in handling a range of uncertainties without significant degradation in performance.

The minimal impact on rise time and steady-state speed error demonstrates that the control strategy can maintain high performance and stability, making it a viable option for applications where reliability and stability are paramount despite the presence of uncertainties. This robustness is crucial for practical applications where conditions can change unpredictably, ensuring that the system remains reliable and stable under varying conditions.

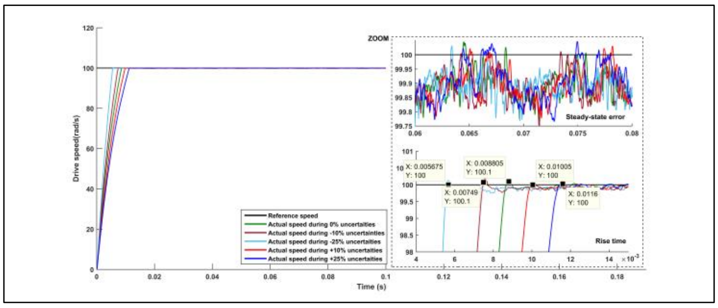

Figure 12: PMSM speed performance under uncertainties.
Source: Authors, (2024).

Table 2: A comparative study of the performance characteristics of the PMSM controller.

Control design	**Performance Characteristics**				
	Rise time (ms) (%)	**THD (%)**	**Speed Stability under disturbance**	**Speed Overshoot under disturbance**	**Ripple Torque (%)**
C-FBLC	40	41.99	Quite	1	-1, +1
SMC-FBLC	10	20.87	Good	0.5	-0.5, +0.5

Source: Authors, (2024).

Figure 14 illustrates that the SMC-FBLC hybrid control approach significantly reduces Total Harmonic Distortion (THD) compared to the conventional C-FBLC design depicted in Figure 13. This reduction in THD is crucial as it translates to improved operational efficiency, where the PMSM system can perform more effectively with less energy loss. Additionally, the enhanced reliability is evident through the system's stable performance and resistance to disturbances, which are critical for long-term operation and maintenance. The minimized electrical noise further contributes to the overall performance enhancement by reducing the interference with other electronic components and systems, leading to smoother and quieter operation.

The comparative analysis in Table 2 provides a detailed examination of these improvements. It shows that the THD levels in the SMC-FBLC approach are markedly lower than those in the C-FBLC design, underscoring the effectiveness of the hybrid control strategy in managing harmonics. Efficiency metrics reveal that the SMC-FBLC system operates with greater efficiency, utilizing energy more effectively and reducing waste. The reliability data highlights the superior robustness of the SMC-FBLC approach, ensuring consistent and predictable performance even under varying operational conditions. Noise reduction figures demonstrate the SMC-FBLC system's ability to minimize electrical noise, which is beneficial for both the motor and the connected electronic systems.

Furthermore, the performance metrics in Table 2 clearly show that the SMC-FBLC hybrid control strategy outperforms the conventional C-FBLC design across multiple key areas, making it the preferable choice for high-performance PMSM applications. These findings confirm the superiority of SMC-FBLC, highlighting its potential for further refinement and broader application in various industrial contexts.

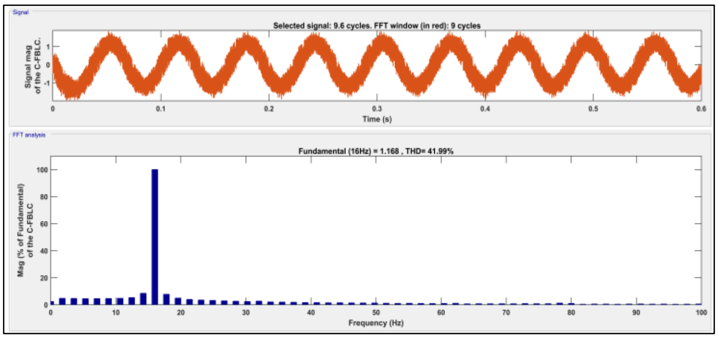

Figure 13: Harmonic analysis of the current of the C-FBLC.
Source: Authors, (2024).

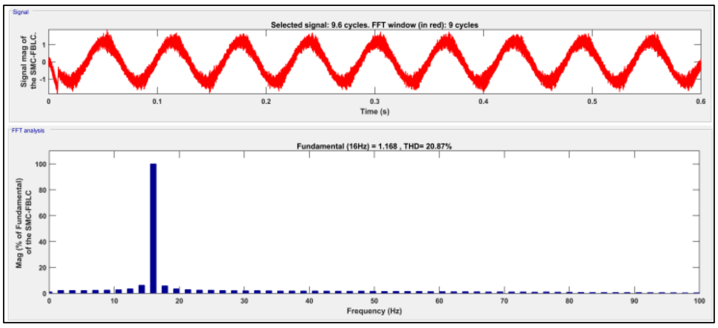

Figure 14: Harmonic analysis of the current of the SMC-FBLC.
Source: Authors, (2024).

V. CONCLUSIONS

This study introduces SMC-FBLC, a hybrid control strategy for PMSMs that integrates Sliding Mode Control (SMC) and Feedback Linearization Control (FBLC). The combined approach leverages the robustness and disturbance rejection capabilities of SMC with the precision and effectiveness of FBLC, resulting in a control method that offers superior performance. The results demonstrate that SMC-FBLC surpasses conventional FBLC (C-FBLC) by achieving faster speed responses, which allows the motor to reach the desired speed more quickly and maintain it more accurately. This enhancement is especially noticeable during rapid acceleration and deceleration phases, providing smoother transitions and greater precision. In terms of error minimization, SMC-FBLC excels by reducing steady-state errors to a negligible level, ensuring that the actual motor speed closely follows the reference speed. This precise control is essential for applications requiring high accuracy.

Additionally, the SMC-FBLC method improves torque characteristics, particularly during speed reversals. This means that the motor can maintain consistent and reliable torque output even when changing directions frequently, enhancing overall system stability and performance. Current regulation is another area where SMC-FBLC shows significant improvement. By ensuring that the motor operates within the desired current limits, the hybrid controller reduces fluctuations and enhances the overall efficiency of the system, leading to lower power losses and improved energy efficiency. The robustness of SMC plays a crucial role in dealing with external disturbances and system uncertainties, allowing SMC-FBLC to maintain stable operation despite variations in load and other external factors. This ensures reliable performance under a wide range of conditions.

Moreover, the analysis of Total Harmonic Distortion (THD) confirms SMC-FBLC's efficiency and quality advantages over C-FBLC. The significant reduction in THD indicates smoother and more efficient motor operation, resulting in less electrical noise and reduced stress on the motor and associated components. This not only improves performance but also extends the lifespan of the motor and its components, enhancing overall system reliability.

VI. AUTHOR'S CONTRIBUTION

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VII. REFERENCES

[1] D. Fu, X. Zhao, and H. Yuan,"High-precision motion control method for permanent magnet linear synchronous motor", IEICE Electronics Express, vol. 18, no. 9, pp. 20 210 097–20 210 097, 2021. https://doi.org/10.1587/elex.18.20210097

[2] B. K. Bose, “Power electronics and motion control-technology status and recent trends”, IEEE Transactions on Industry Applications, vol. 29, no. 5, pp. 902–909, 1993. https://doi.org/10.1109/28.245713

[3] M. Nicola, C.-I. Nicola, and D. Selis, teanu, “Improvement of pmsm sensorless control based on synergetic and sliding mode controllers using a reinforcement learning deep deterministic policy gradient agent”, Energies, vol. 15, no. 6, p. 2208, 2022. https://doi.org/10.3390/en15062208

[4] J.-W. Jung, V. Q. Leu, T. D. Do, E.-K. Kim, and H. H. Choi, “Adaptive pid speed control design for permanent magnet synchronous motor drives”, IEEE Transactions on Power Electronics, vol. 30, no. 2, pp. 900–908, 2014. https://doi.org/10.1109/TPEL.2014.2311462

[5] W. Liu, S. Chen, and H. Huang, “Adaptive nonsingular fast terminal sliding mode control for permanent magnet synchronous motor based on disturbance observer”, IEEE Access, vol. 7, pp. 153 791–153 798, 2019. https://doi.org/10.1109/ACCESS.2019.2948945

[6] H. K. Khalil, “Control of nonlinear systems”, 2002.
[7] H. J. Chiel and P. J. Thomas, “Special issue on applied neurodynamics: from neural dynamics to neural engineering”, vol. 8, no. 6. IOP Publishing, 2011, p. 060201. https://doi.org/10.1088/1741-2552/8/6/060201

[8] D. Karboua, T. Belgacem, Z. H. Khan, and C. Kellal, “Robust performance comparison of pmsm for flight control applications in more electric aircraft”, Plos one, vol. 18, no. 7, p. e0283541, 2023. https://doi.org/10.1371/journal.pone.0283541

[9] K. Zhou, M. Ai, D. Sun, N. Jin, and X. Wu, “Field weakening operation control strategies of PMSM based on feedback linearization”, MDPI, 2019, vol. 12, no. 23. https://doi.org/10.3390/en12234526

[10] K. Mei and S. Ding, “Second-order sliding mode controller design subject to an upper-triangular structure”, IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 51, no. 1, pp. 497–507, 2018. https://doi.org/10.1109/TSMC.2018.2875267

[11] Z. Zhou, B. Zhang, and D. Mao, “Robust sliding mode control of pmsm based on rapid nonlinear tracking differentiator and disturbance observer,” Sensors, vol. 18, no. 4, p. 1031, 2018. https://doi.org/10.3390/s18041031

[12] P. Pillay and R. Krishnan, “Modeling of permanent magnet motor drives”, IEEE Transactions on industrial electronics, vol. 35, no. 4, pp. 537–541, 1988. https://doi.org/10.1109/41.9176

[13] R. Abdessemed, “Modélisation et simulation des machines électriques: électrotechnique”, Ellipses, 2011.

[14] Y.-G. Huangfu, “Research of nonlinear system high order sliding mode control and its applications for pmsm”, Ph.D. dissertation, Northwestern Polytechnical University (Chine), 2010.

[15] D. Karboua, T. Belgacem, Z. H. Khan, C. Labiod, and I. K. Ibraheem, “Toward an optimal twisting-sliding mode control of a three-phase pmsm for electric vehicles”, Advances in Mechanical Engineering, vol. 15, no. 9, p. 16878132231198664, 2023. https://doi.org/10.1177/16878132231198664

[16] J. Guldner and V. Utkin, “The chattering problem in sliding mode systems”, in Proc. 14th Int. Symp. of Mathematical Theory of Networks and Systems (MTNS), 2000.

[17] J.-J. E. Slotine, W. Li et al., “17. Prentice hall Englewood Cliffs”, NJ, 1991, vol. 199, no. 1.

[18] K. Djaloul, T. Belgacem, I. Atif, C. Youcef, M. Toufik, and D. B. Ouadeh, “High order sliding mode control based on a new terminal strategy applied on the speed permanent magnet synchronous machine”, in 2023 XIX International Scientific Technical Conference Alternating Current Electric Drives (ACED). IEEE, 2023, pp. 1–6. https://doi.org/10.1109/ACED57798.2023.10143468