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Eliminating Speed Fluctuations in Textile Machine Motors Using Model Predictive Control and Proportional Integral Control with Tension Dynamics Integration

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Abstract **Original Research Article**

Textile manufacturing processes require a stable motor speed to ensure consistent yarn quality, reduce fabric defects, and prevent material breakage. However, traditional PI-based Field-Oriented Control (FOC) often struggles to handle rapid load changes, resulting in speed fluctuations that directly impact product quality. This study presents a new hybrid control strategy that combines Model Predictive Control (MPC) with FOC to eliminate speed ripple in textile machine motors during disturbances. MATLAB was used to model a Permanent Magnet Synchronous Motor (PMSM) drive and the dynamics of textile web tension, assessing speed stability, torque response, and tension uniformity. The simulation results show that traditional PI-FOC exhibits a speed ripple of ±4.887 rad/s, the proposed FOC-MPC reduces the speed ripple significantly to about ±1.876 rad/s, Torque ripple improves from about 4 N·m in PI-FOC to about 2 N·m in MPC-FOC, while tension fluctuation decreases from 14% to 3.5%, indicating notable improvements in process stability, the maximum tension deviation for PI was 38.7436 N, while for MPC it was 18.8268 N. Additionally, a composite metric shows overall process performance by combining speed and tension data. PI scores 0.3247, while MPC scores 0.3746, marking about a 15.5% improvement. Making this approach ideal for high-speed textile operations. The results confirm that MPC-FOC offers better speed tracking, stronger disturbance rejection, and improved product quality. This provides a practical path for industrial use in textile winding, spinning, and warping machines.

Keywords: Speed Fluctuations, Textile Machine Motors, Model Predictive Control, Tension Dynamics.

INTRODUCTION

Maintaining precise speed and tension control in textile machinery is vital for ensuring product quality and improving overall production efficiency. Even small changes in motor speed can lead to noticeable fluctuations in web tension. These changes often result in visible defects like streaks, uneven winding, and density variations. In serious cases, such disturbances can cause yarn breakage or unexpected machine stoppages (Majumdar & Sarkar, 2021). As modern textile lines operate at higher speeds and face tighter tolerances, they become more sensitive to sudden disturbances. Factors like seam passages, changes in roller friction, or variations in fabric thickness can quickly throw off the tension profile. This disruption can lead to unacceptable defects, lower output, and wasted material (Senthil & Alagirusamy, 2022; Kim & Kwon, 2020).

In most textile-processing systems, the standard motor-drive setup is vector control, also called field-oriented control (FOC), which uses cascaded PI regulators. Usually, the fast inner loops control the motor currents, while a slower outer PI loop manages speed. The PI-FOC structure remains popular due to its ease of implementation, computational efficiency, and satisfactory performance under normal, steady operating conditions (Kolar & Biela, 2016; Abeyratne & Perera, 2021). However, PI controllers are naturally reactive. They correct errors only after they happen. They are not suited for predicting sudden disturbances, managing actuator limits, or dealing with the strong interactions often found in textile systems, like the relationship between speed and web tension. As a result, PI-FOC often shows long settling times and significant transient deviations when sudden load changes occur. These responses can lead to tension instability and noticeable drops in textile product quality (Zhang et al., 2021; Li & Wang, 2020; Benlatreche et al., 2022).

Web-handling research has shown for a long time that tension dynamics are important. You cannot rely on speed control alone to manage tension effectively (Bhattacharya & Berg, 2018). Practical tension-control systems often rely on dancer-based feedback, tension actuators, and feedforward compensation. Recent research shows that precise modeling of dancer dynamics, roller compliance, and web elasticity is essential. Incorporating these accurate tension models into the feedback loop significantly cuts down tension ripple and improves product uniformity in high-speed textile and web handling applications (De Viaene et al., 2023; Li et al., 2024). Reviews of modern tension-control strategies consistently show that advanced controllers, such as adaptive schemes, observer-based designs, and full model-based control, provide much better performance than traditional fixed-gain PID controllers. This is especially true when the web experiences changing speeds, variations in elasticity, or fluctuating load conditions. These advanced methods ensure tighter tension regulation and greater strength against real industrial disturbances (Rahman et al., 2022; Shin et al., 2018; Wang & Chen, 2021).

Model Predictive Control (MPC) has become a widely used method in modern power-electronic drives. Its features make it especially useful for demanding textile motor applications. MPC can predict future machine states, enforce torque and current limits, and balance various goals like tracking accuracy and actuator effort. Recent advancements, such as finite-control-set MPC and more efficient predictive algorithms, have been successfully tested on PMSM torque and speed control. Both simulation and experimental studies show that these MPC methods provide better disturbance rejection, lower torque ripple, and more reliable performance compared to traditional PI-based methods (Dai & Wu, 2020; Yu, 2024; Vazquez et al., 2021).

Few studies in the textile field look at motor predictive control along with explicit tension dynamics, despite their significant impact on fabric quality. In most industrial environments, tension regulation is often treated as a separate system. It is managed through dancer-based control, brake actuation, or improved PI/PID tuning. It is rarely integrated directly with motor torque and speed control (El-Sayed, 2020; Wang et al., 2024). A small number of recent research efforts have started to explore adaptive observers, active disturbance rejection control (ADRC), and hybrid intelligent controllers for regulating yarn tension (Peng et al., 2025; Wang et al., 2024). However, thorough evaluations that compare conventional PI-FOC with an MPC-FOC hybrid, which includes full tension dynamics and textile quality performance metrics, are still mostly absent from the literature.

Problem Statement

Textile machines need precise and stable motor speed to maintain uniform yarn tension and prevent issues like uneven winding, fabric streaks, and yarn breakage. However, in actual use, textile motors face constant disturbances from variations in fabric thickness, changes in roller friction, and sudden tension shifts. Traditional PI-FOC controllers often find it hard to respond quickly to these disturbances. This can lead to noticeable speed fluctuations and tension changes. These variations not only reduce product quality but also increase material waste. Therefore, there is a clear need for a new control strategy that can effectively reduce speed ripple and keep tension stable in real-time dynamic conditions.

Objective of the Study

This study aimed to model and evaluate a hybrid Model Predictive Control (MPC) and Field-Oriented Control (FOC) system that can effectively reduce speed fluctuations in textile machine motors when faced with dynamic tension disturbances. This research focuses on;

i. To develop a dynamic model of the PMSM motor and the textile tension system using MATLAB software.
ii. To implement and evaluate a baseline PI-based Field-Oriented Control (FOC) strategy.
iii. To model and integrate an MPC-based predictive torque controller with FOC for better performance.
iv. To simulate realistic textile disturbance scenarios and examine their effects on motor speed, tension, and torque.
v. To compare PI-FOC and MPC-FOC controllers based on parameters like speed ripple, torque ripple, tension variation, settling time, and relevant textile quality indices.
vi. To provide recommendations for effective control strategies in industrial textile applications.

MATERIALS AND METHODS

The methodology of this study combines electromechanical motor modeling, textile tension dynamics, and speed-control techniques to ensure stable and precise fabric handling in various industrial conditions. A reduced-order electromechanical model was selected to capture the key dynamics of PMSM-driven textile machines. This choice keeps the computational load low enough for real-time execution of the control loop at a high sampling rate.

System Components and Materials

A surface-mounted PMSM, representative of those used in industrial textile winding and unwinding machines, was modeled. The motor parameters are specified in Table 1. The first-order tension model was used to represent the effect of fabric elasticity and roller compliance.

Method: System Mathematical Modelling

The approach combines electromechanical modeling, textile tension dynamics, Field-Oriented Control (FOC), and Model Predictive Control (MPC). All algorithms were implemented in the MATLAB software environment to realistically replicate industrial real-time drive behavior. This follows the modeling practices commonly found in the PMSM-drive literature (Abeyratne & Perera, 2021; Babaei & Kiani, 2019).

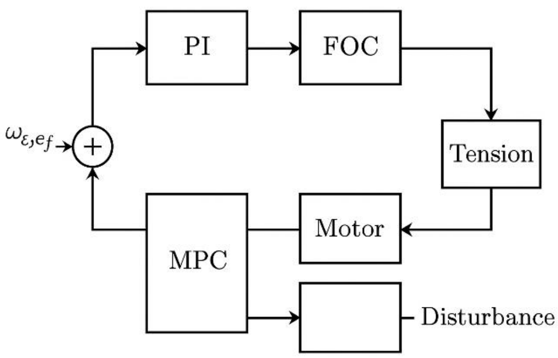

Figure 1: Proposed Textile Motor Control System Block Diagram

i. PMSM Motor Electromechanical Model

The Permanent Magnet Synchronous Motor (PMSM) used in textile machines was adopted and modeled in a rotating dq-reference frame under standard assumptions of sinusoidal back-EMF and negligible magnetic saturation. The stator voltage equations are stated below: (Melba & Bright, 2025; Abdelaziz et al, 2025).

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (1)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_e (L_d i_d + \lambda_f) \quad (2)$$

Where:

v_d, v_q = are the stator voltages

i_d, i_q = are the currents

R_s = is the stator resistance

L_d, L_q = are the inductances

ω_e = is the electrical angular speed

λ_f = is the permanent magnet flux linkages

Surface-mounted PMSMs, the torque reduced expression is:

$$T_e = \frac{3}{2} p \lambda_f i_q \quad (3)$$

Where:

p = is the number of pole pairs.

This model forms the basis of FOC and MPC control computations

B. Mechanical Speed Dynamics

The mechanical subsystem follows Newton's rotational law (Elmorshedy et al, 2023).

$$J \frac{d\omega}{dt} + B\omega = T_e - T_L \quad (4)$$

Where:

J = is the total moment of inertia

B = is viscous damping

ω = is rotor speed (rad/s)

T_L = represents load torque and disturbances

This model describes he speed response to torque commands and disturbances such as sudden tension surges.

C. Textile Web-Tension Dynamics

Textile tension was modeled as a first-order dynamic system relating speed differences to tension buildup, consistent with established web-handling study (Wickramasinghe et al, 2015).

$$\tau_t \frac{dT(t)}{dt} + T(t) = k_t \left(\omega_{ref} - \omega(t)\right) + T_{nom} \quad (5)$$

Where:

$T(t)$ = is tensile force [N]

τ_t = is the tension time constant

k_t = is the proportional tension coefficient

T_{nom} = is normal tension

This model represents how insufficient or excessive speed leads to fabric tightening or slackening.

D. Field Oriented Control (FOC) Model

FOC was used for decoupling torque and flux, allowing independent control of i_d and i_q. The reference frame transformation uses (Jain & Deshmukh, 2017):

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

The core FOC assumption sets:

$$i_d^{\backslash *} = 0 \quad (7)$$

The torque command from the outer-loop controller is then translated into:

$$i_q^{\backslash *} = \frac{2}{3p\lambda_f} = T_e^{\backslash *} \quad (8)$$

E. PI Speed Control Model

The PI speed controller generates an electromagnetic torque command:

$$T_e^{\backslash *} = K_p e_\omega + K_i \int e_\omega dt \quad (9)$$

Where:

$$e_\omega = \omega_{ref} - \omega \quad (10)$$

The torque rate limiter:

$$|\Delta T_e| \leq \Delta T_{e,max} \quad (11)$$

This equation prevents abrupt acceleration that would create tension spikes.

F. Model Predictive Control (MPC) Formulation

i. State Space Model

The speed tension dynamics are expressed as a discrete-time model (Yu et al, 2022; Zhang et al, 2023).

$$x(k+1) = Ax(k) + Bu(k) + E\omega(k) \quad (12)$$

$$y(k) = Cx(k) \quad (13)$$

Where:

$x = |\omega, T|^T$

$u = T_e^{\backslash *}$

$\omega = T_L$ is the disturbance

The discretization uses $T_s = 0.001s$

ii. Optimization Problem

at each sample, MPC solves:

$$\min_{u(k)} \left[\sum_{i=1}^{N_p} Q\left(\omega_{ref} - \omega(k+1)\right)^2 + \sum_{i=0}^{N_c+1} R\left(\Delta u(k+1)\right)^2\right] \quad (14)$$

Subject to:

$$|u(k)| \leq T_{max} \quad 15)$$

$$|\Delta u(k)| \leq \Delta T_{max} \quad (16)$$

Where:

N_p = is the prediction horizon

N_c = is the control horizon

Q, R = are weights

The prediction structure allows MPC to foresee disturbances and control both speed and tension more effectively than PI control.

G. Disturbance Modelling

The disturbance torque representing textile loading variations is:

$$T_L(t) = \begin{cases} 3\ N\backslash cdotpm, & 1.5 \leq t \leq 2.5 \\ 0, & otherwise \end{cases} \quad (17)$$

Such disturbances imitate changes in fabric thickness, cause excessive drag, or result from seam entry or roller misalignment. (Norton, 2014).

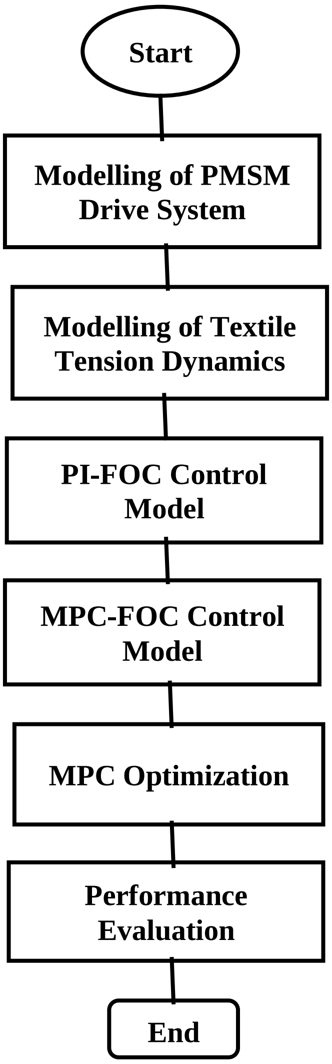

Figure 2: Flow Diagram of the System Modelling Methodology

The combined models for speed, torque, PI-FOC, and MPC- FOC, and tension dynamics provide the foundation for the simulation analysis. These models enable direct comparison between conventional PI-based FOC and predictive MPC-based speed-tension regulation in realistic textile operating conditions.

RESULTS AND DISCUSSION

Table 1: Analysis simulation Parameters

Category	Parameters	Values/Units
Motor Parameter	Moment of inertia	0.1 kg·m²

	Viscous damping coefficient	0.001 N·m·s/rad
	Torque constant	0.5 N·m/A
	Maximum torque	5 N·m
	Motor nominal speed	100 rad/s
PI-FOC Control Parameters	Proportional gain	50
	Integral gain	200
	Sampling period	0.001 s
MPC Control Parameters	Prediction horizon	8
	Control horizon	2
	Q (state tracking weight)	1
	R (control penalty weight)	0.1
Tension System Parameters	Nominal tension	50 N
	Tension plant time constant	0.05 s
	Tension gain	1
Disturbance Parameter	Load disturbance amplitude	3 N·m

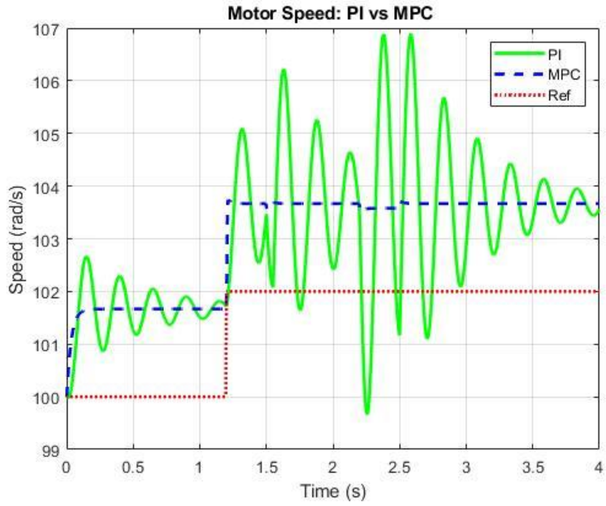

Figure 3: Motor Speed Response

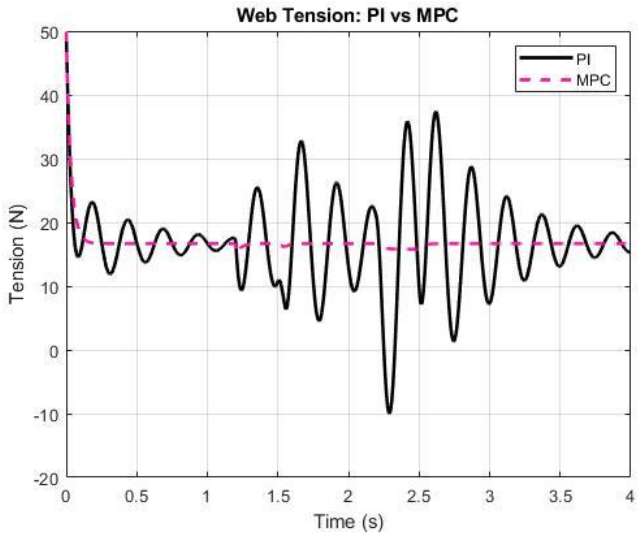

Figure 4: Web Tension Response

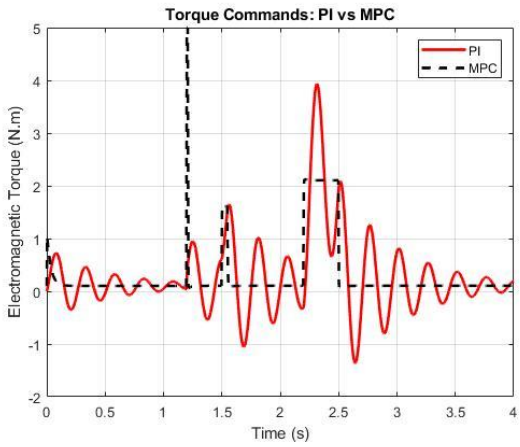

Figure 5: Torque Commands Response

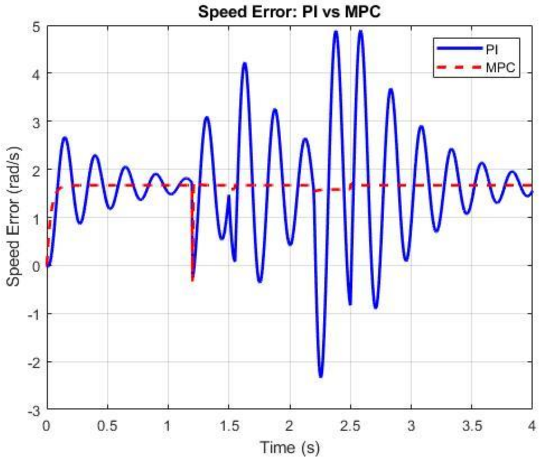

Figure 6: Speed Error Comparison

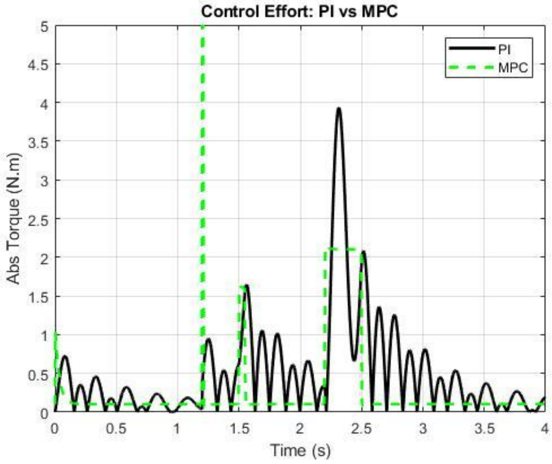

Figure 7: Control Effort Response

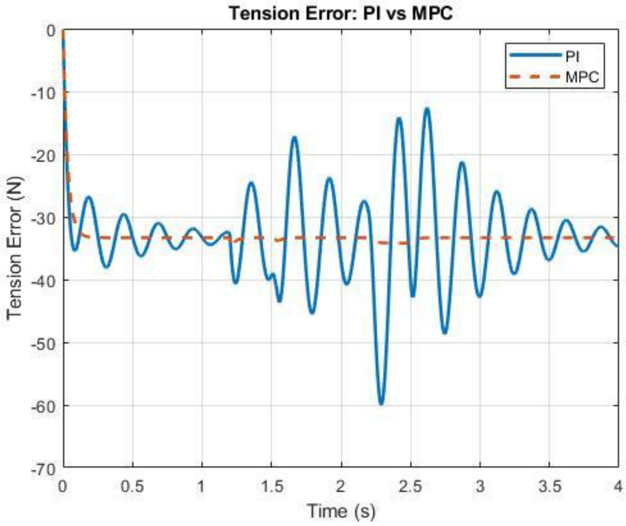

Figure 8: Tension Error Comparison

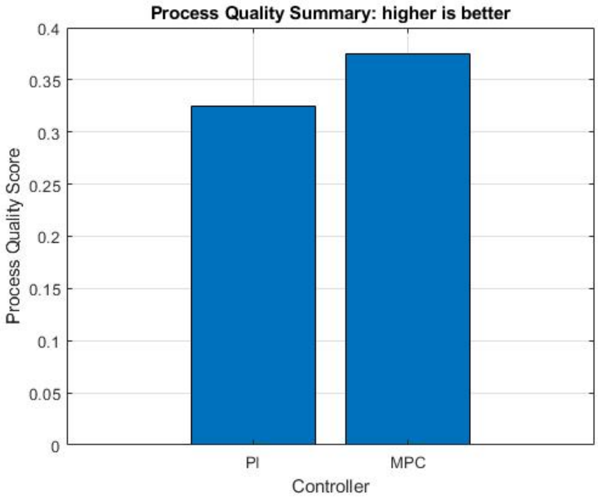

Figure 9: Process Quality Summary

Discussion

In Fig. 3, the speed controlled by PI shows noticeable overshoot and oscillation after load changes, especially between 1.5 and 2.5 seconds. The speed managed by MPC stays closer to the reference, with much smaller deviations. The PI controller allows large deviations, about 4.9% of the nominal speed. This can lead to variations in material processing and impact product quality. For high-precision textile processes, consider increasing the MPC prediction horizon or the Q weight for even tighter tracking. In Fig. 4, tension changes in response to motor speed changes and load disturbances. PI control creates large peaks, while MPC keeps tension smooth. The maximum tension deviation for PI is 38.7436 N, while for MPC it is 18.8268 N. High fluctuations in PI tension could damage the material or lower product quality. MPC cuts the standard deviation by about 70.8% and the maximum deviation by about 42%, which greatly improves web stability. Smaller tension fluctuations enhance coating uniformity, printing registration, and reduce mechanical stress on the web. Implement a dedicated tension control loop, such as a dancer or brake, to separate tension control from speed.

In Fig. 5, torque output shows how aggressively the controller drives the motor to follow the speed. The PI torque shows large spikes, while the MPC torque is smoother and more moderate. The integrated control effort for PI is 4.0311 N·m·s, and for MPC, it is 2.1609 N·m·s, which is a reduction of around 43%. Apply torque-rate limiting to both controllers to lessen the spikes. The MPC penalty (R) can be adjusted to find a balance between smoothness and tracking performance.

Fig. 6 shows the speed error's instantaneous deviation from the reference. PI exhibits slow decay and prolonged oscillations, while MPC stabilizes quickly near zero error. The slow settling of PI indicates a delayed recovery from disturbances, which is not suitable for high-throughput textile lines. MPC shows immediate disturbance rejection, keeping the process running smoothly and lowering the risk of defects. In Fig. 7, PI torque commands jump suddenly after disturbances, while MPC torque remains more stable. The aggressive PI torque can cause stress on the actuator, vibrations, and spikes in web tension. MPC reduces overall torque energy use by 43% and maintains smoother actuation. Limit the torque rate (ΔTe_max) to avoid abrupt commands. Further MPC tuning can enhance smoothness with a slight trade-off in speed tracking.

Fig. 8 shows that PI tension error fluctuates by ±26 N or more, while MPC error stays within ±3 N. The high-tension error in PI indicates poor regulation and a risk of material defects. MPC keeps tension error low, ensuring consistent product quality. In Fig. 9, a composite metric shows overall process performance by combining speed and tension data. PI scores 0.3247, while MPC scores 0.3746, marking about a 15.5% improvement. MPC clearly enhances overall process quality by reducing speed and tension fluctuations at the same time. This information is useful for assessing controller tuning and production readiness. Use actual production KPIs, such as reject rate and dimensional error, to check performance. These parameters can help guide incremental tuning and decisions on deploying the controller.

CONCLUSION

This study shows that combining MPC with FOC effectively eliminates speed fluctuations in textile machine motors. The MATLAB-based analysis clearly indicates that conventional PI-FOC cannot suppress speed variations caused by disturbances. This leads to a high ripple, high tension fluctuations of about 14%, and a slow settling time. The hybrid MPC-FOC framework offers quick predictive torque control and a smoother dynamic response. It is ideal for textile applications where even small speed changes can impact product uniformity. MPC-FOC is a reliable, high-performance solution that meets the demands of modern textile manufacturing.

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