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Design of a Model Predictive Control for Speed Control of a Motor Drive System in an Electric Oil Palm Cutter

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ABSTRACT: *This study presents the design of a speed control system for a Motor Drive Permanent Magnet Synchronous Motor (MDPMSM) to achieve a faster and more stable dynamic response in an electric oil palm cutter, supporting the harvesting process of oil palm fruit. Conventional control methods such as Proportional-Integral (PI) controllers, which are commonly applied, still face challenges in parameter tuning and exhibit high sensitivity to speed variations in cutting operations. To overcome these limitations, this research proposes a Model Predictive Control (MPC)-based speed regulation system integrated into a Field-Oriented Control (FOC) structure for a encoderless MDPMSM. The mathematical model of the motor serves as the foundation for designing the predictive algorithm, which can estimate motor speed behavior in real time. Performance evaluation was conducted through simulations under step-response conditions involving sudden speed changes, as well as ramp-response conditions. The simulation results were compared with those of the PI controller to assess the system's ability in achieving steady-state time, overshoot, and undershoot. The results demonstrate that the MPC-based controller significantly enhances system performance, achieving up to a 60% reduction in settling time, an 84% decrease in overshoot, and a 58% improvement in recovery capability. Moreover, under ramp-response testing, the MPC-based system exhibited a more linear and responsive speed-tracking performance. Therefore, the proposed MPC control design proves to be effective in improving the accuracy and stability of encoderless MDPMSM speed control systems and serves as a reliable alternative for high-precision motor drive control applications, particularly in electric oil palm cutting systems.*

Keywords: *Model Predictive Control, MDPMSM, Vector Control, Speed Control, Electric Oil Palm Cutter*

1. INTRODUCTION

The Motor Drive Permanent Magnet Synchronous Motor (MDPMSM) is one of the most widely used electric motors drive in various applications such as manufacturing industries, electric vehicles, renewable energy systems, military transportation, and agro-industrial technologies. This motor features a robust structure, high power efficiency, and excellent torque density, making it a reliable choice for high-performance motion control systems in industrial environments (Omeje et al., 2024). One notable application of MDPMSMs in the agro-industrial sector is as the primary drive in Electric Oil Palm Cutters, which require fast, stable, and efficient speed control systems to support the harvesting process of oil palm fruit. The Field-Oriented Control (FOC) method is a widely applied vector control technique designed to enhance PMSM performance. The system consists of two crucial components, namely speed control and current control, both of which play essential roles in achieving optimal motor control accuracy (Abdelaziz et al., 2024). The speed control loop is expected to respond rapidly to sudden condition changes and disturbances (Mahmoudi et al., 2024). The output of this loop serves as the input to the current control system. Hence, the more responsive and accurate the speed controller is, the better the overall performance of the MDPMSM current control system will be (Orłowska-Kowalska et al., 2022).

Research on MDPMSM speed control continues to evolve to meet industrial requirements. The Proportional-Integral (PI) controller is commonly used in closed-loop speed control systems because it provides robustness against disturbances during motor operation (Salman et al., 2023). However, the system's response depends heavily on properly tuned proportional and integral constants. Parameter tuning rules such as the Ziegler–Nichols (Khanh et al., 2023) and Cohen–Coon methods have been proposed (Adeoye et al., 2019), but they still require a time-consuming trial-and-error process (Odo et al., 2019). Fuzzy logic-based approaches have been implemented to adaptively adjust proportional and integral gains (Khanh et al., 2023). This approach allows the system to adapt its parameters under sudden disturbances to maintain fast and stable responses. Although fuzzy control can deliver good dynamic performance and reduce the need for retuning, the design of membership functions still requires accurate initial parameters. Furthermore, Artificial Intelligence (AI) and Machine Learning (ML) techniques have also been applied to optimize PI parameters in MDPMSM control systems (Santos et al., 2019). However, these methods often increase the complexity of the closed-loop control system. To overcome these limitations, this study proposes the implementation of Model Predictive Control (MPC) as a replacement for the conventional PI controller within the FOC structure for MDPMSM speed control. The proposed system eliminates the dependency on manually tuned proportional and integral parameters. Moreover, the control model is derived from the motor's torque equations, simplifying the implementation and enhancing reliability. Since the current control loop is directly related to the decoupling control mechanism in FOC, the proposed torque-based predictive model is expected to yield faster transient response and improved steady-state performance. In addition, vector control implementation, rotor position and speed information are crucial components. Mechanical sensors are typically used to obtain this information; however, they increase production costs, wiring complexity, and system dimensions. They may also cause mechanical losses and exhibit limited resolution, especially at low speeds. Therefore, this study adopts a encoderless control approach using the High-Frequency Injection (HFI) technique to estimate rotor position and speed (Benevieri et al., 2023).

Overall, this research aims to design a MPC-based speed control for MDPMSM to enhance motor drive control performance in electric oil palm cutting applications, particularly under sudden speed variation conditions evaluated through step and ramp response tests. Accordingly, the main contributions of this study can be summarized as follows:

1. The design of a Model Predictive Control (MPC) system for s speed control of a MDPMSM applied to an electric palm oil cutter system.
2. Minimization of parameter tuning difficulties commonly encountered in conventional PI controller design.
3. Enhancement of control response speed to achieve steady-state conditions during transient operations.

The rest of this paper is organized as follows. Section 2 describes the fundamental equations of the proposed design of speed control MPC-based for MDPMSM in an electric palm oil cutter. Section 3 presents the experimental results and performance analysis of the control system. Finally, Section 4 concludes the paper with a summary of key findings.

2. MPC-Based FOC Design for Speed Control Motor Drive in an Electric Palm Oil Cutter

The FOC technique is one of the most efficient motor control strategies used under dynamic operating conditions suitable for varying speed in an electril palm cutter. The MDPMSM is among the types of motor drive systems that employ this technique to achieve optimal performance and high efficiency. Mathematically, the dynamic voltage equations of MDPMSM in the direct and quadrature (dq) reference frame under vector control can be expressed as follows:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s & -\omega_e L_q \\ \omega_e L_d & R_s \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \varphi_f \end{bmatrix} \quad (1)$$

Where $v_d, v_q, i_d, i_q, L_d, L_q$ and φ_f represent the dq-axis stator voltages, dq-axis currents, stator resistance, dq-axis inductances, and the permanent magnet flux linkage, respectively. The electromagnetic torque of MDPMSM in the dq reference frame can be expressed as in Equation (2), while the electromechanical dynamic characteristics are shown in Equation (3):

$$T_e = \frac{3}{2} P_n \left[\varphi_f i_q + (L_d - L_q) i_d i_q \right] \quad (2)$$

$$T_e - T_L = J \frac{d\omega_m}{dt} + B\omega_m \quad (3)$$

Where $T_e, T_L, J,$ and B denote the electromagnetic torque, load torque, total rotor and load inertia, and the viscous friction coefficient, respectively. The mechanical angular velocity ω_m is obtained from the relationship $\omega_m = \omega_e / P_n$, where P_n is the number of motor pole pairs.

In vector control, a decoupling system is implemented, in which the rotor position, rotor speed, and motor inductance parameters are assumed to be well known. The cross-coupling effect in MDPMSM control must also be taken into account to achieve optimal system performance. Both the speed and current control loops play crucial roles in the design of MDPMSM vector control. Figure 1 illustrates the MDPMSM vector control system that employs a conventional PI controller for electric palm oil cutter. In detail, the vector control method consists of two main stages: speed control and current control. Speed control plays an important role in achieving effective current control, which directly affects the performance of the overall vector control system. Therefore, this study focuses on speed control, which is commonly implemented using a PI controller. However, to obtain a faster dynamic response, a predictive-based control system is proposed to improve the dynamic performance of the drive.

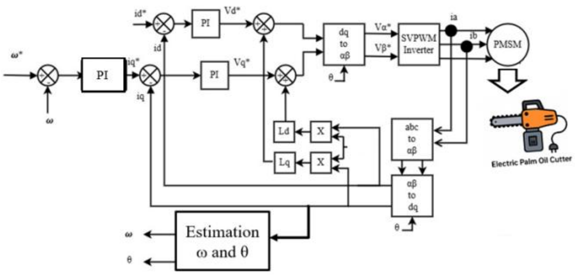

Figure 1. Modelling systems MDPMSM Vector Control Using PI Speed Controller for Electric Palm Oil Cutter

The PI controller is commonly used in vector control systems, also known as dq-axis FOC, due to its robust structure. However, the control performance heavily depends on selecting appropriate proportional and integral parameters (K_p and K_i). Consequently, determining these parameters typically requires a time-consuming process involving multiple trial-and-error experiments to achieve optimal results.

To overcome this limitation, this study proposes an MPC-based predictive control approach as an alternative to the PI controller for MDPMSM speed control. This approach eliminates the need for manual tuning of K_p and K_i parameters. The MPC system for MDPMSM speed control is designed based on the speed differential in Equation (3), discretized using a first-order differential approximation. The discrete-time model of the MPC-based speed control can thus be expressed as:

$$\begin{cases} x_0(k+1) = A_m x_0(k) + B_m \Delta u_0(k) \\ y_0(k) = C_m x_0(k) \end{cases} \quad (4)$$

where

$$A_m = \begin{bmatrix} a & 0 \\ ca & 1 \end{bmatrix}; B_m = \begin{bmatrix} b \\ cb \end{bmatrix}; \ C_m = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (5)$$

$$x_0(k+1) = \begin{bmatrix} \Delta\omega_m(k+1) \\ \omega_m\,(k+1) \end{bmatrix}; x_0(k) = \begin{bmatrix} \Delta\omega_m(k) \\ \omega_m\,(k) \end{bmatrix} \quad (6)$$

$$\Delta u_0(k) = \Delta i_q(k); \ y_{0-}(k) = \omega_m(k); a = -\frac{B}{J}T_s \,; b = \frac{3p_n\varphi_{fT_z}}{2J}; c = 1 \quad (7)$$

Meanwhile, the adopted HFI technique has become one of the most widely used methods in the development of encoderless control technology, which continues to attract significant research interest. This technique estimates rotor position and speed for vector control implementation and is particularly suitable for low-speed operation, where nonlinear effects, dynamic disturbances, and mechanical losses often degrade the performance of sensor-based vector control systems. Since HFI operates in the low-speed region, the motor drive PMSM voltage equation in (1) can be rewritten as:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (8)$$

During high-frequency signal injection, the motor's electrical frequency is much lower; therefore, Equation (8) can be sim plified into an inductance form as follows:

$$\begin{bmatrix} v_{dh} \\ v_{qh} \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \quad (9)$$

The injected high-frequency voltage signal in the estimated dq-frame can be expressed as:

$$HF^i = \begin{bmatrix} \hat{v}_{dh} \\ \hat{v}_{qh} \end{bmatrix} = \ u_{inj} \begin{bmatrix} cos\,(\omega_{inj}t) \\ 0 \end{bmatrix} \quad (10)$$

Using the rotational transformation matrix:

$$T^R = \begin{bmatrix} cos(\Delta\theta) & sin(\Delta\theta) \\ -sin(\Delta\theta) & cos(\Delta\theta) \end{bmatrix} \quad (11)$$

The resulting current components after high-frequency injection can be written as:

$$p\begin{bmatrix}\hat{\imath}_{dh}\\ \hat{\imath}_{qh}\end{bmatrix} = T^{R^{-1}} \begin{bmatrix}\frac{1}{L_d} & 0\\ 0 & \frac{1}{L_q}\end{bmatrix} u_{inj} \begin{bmatrix}cos(\Delta\theta)\ cos\ (\omega_{inj}t)\\ -sin(\Delta\theta)\ cos\ (\omega_{inj}t\end{bmatrix} \quad (12)$$

Where u_{inj} and ω_{inj} denote the amplitude and frequency of the injected voltage signal. When the high-frequency signal is injected along the estimated d-axis, rotor position information can be derived from the induced current signal, as shown below:

$$\begin{bmatrix}\hat{\imath}_{dh}\\ \hat{\imath}_{qh}\end{bmatrix} = \frac{u_{inj}\sin(\omega_{inj}t)}{\omega_{inj}L_dL_q} \begin{bmatrix}L_q\cos^2\Delta\theta + L_d\sin^2\Delta\theta\\ \frac{\sin(2\Delta\theta)}{2}\left(L_q - L_d\right)\end{bmatrix} \quad (13)$$

$$p\begin{cases}\hat{\imath}_{dh} = \left(\frac{u_{inj}\left(L_q + L_d\right)}{2\omega_{inj}L_dL_q} + \frac{u_{inj}\left(L_q - L_d\right)}{2\omega_{inj}L_dL_q}\cos\left(2\Delta\theta\right)\right)\sin\left(\omega_{inj}t\right)\\ \hat{\imath}_{qh} = \frac{u_{inj}\left(L_q - L_d\right)}{2\omega_{inj}L_dL_q}\sin(2\Delta\theta)\sin\left(\omega_{inj}t\right)\end{cases}$$

Based on the principle of high-frequency injection, the value of $\Delta\theta$ is extracted to estimate the rotor position by detecting the $\hat{\imath}_{qh}$ current and demodulating it with the $\sin\left(\omega_{inj}t\right)$ signal. The rotor position information contained within the current amplitude can be obtained when $\Delta\theta$ converges to zero. Through modulation and heterodyning, the position error signal can then be used in a closed-loop system with a PI controller to estimate the rotor position and speed, as expressed in the following equations:

$$f\Delta\theta = LPF\left(\hat{\imath}_{qh}\ \sin\left(\omega_{inj}t\right)\right) \quad (14)$$

$$\widehat{\omega} = K_P\Delta\theta(t) + \int K_I\Delta\theta(t)\ dt \quad (15)$$

$$\hat{\theta} = \int \widehat{\omega}\ dt \quad (16)$$

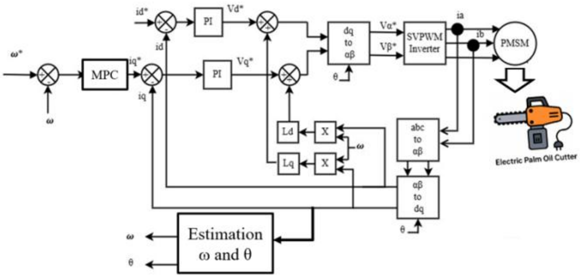

Figure 2. Proposed Modelling systems MDPMSM Vector Control Using MPC Speed Controller for Electric Palm Oil Cutter

As shown in Figure 2, the proposed encoderless MDPMSM vector control system employs MPC-based speed control, where critical information about rotor position and speed is estimated through extracted signals resulting from high-frequency injection. In this system, the injection frequency is set to ten times the motor's fundamental frequency to facilitate low-pass filter performance in extracting rotor position information. The MPC-based speed controller is selected due to its capability to evaluate the system's dynamic response through step and ramp speed variations, which will be discussed in the following section. The proposed control approach is further implemented in an Electric Palm Oil Cutter system to ensure precise and stable motor speed control during cutting operations, thereby improving efficiency and reliability in palm fruit harvesting applications.

3. RESULTS AND DISCUSSION

This section presents a comparison of the results obtained from the simulation of a speed control MDPMSM system applied to an Electric Palm Oil Cutter, using two control methods, namely PI and MPC. The simulation results are illustrated in the form of speed response graphs corresponding to reference changes, to facilitate the performance analysis of the system under step and ramp responses. Furthermore, a comprehensive comparison is conducted, covering key dynamic parameters such as rise time, settling time, overshoot, and undershoot, to evaluate the superiority of the proposed control method in achieving response stability during transient conditions.

First of all, the simulation results of the motor speed response to reference speed variations, which are gradually increased from 0–50 rev/min and subsequently to 100 rev/min. The graph compares the system performance between the PI and MPC controllers against the reference signal denoted as (Speed_Reff). In general, both control methods can follow the changes in reference speed effectively. However, there are significant differences in their dynamic characteristics, particularly in rise time, settling time, as well as overshoot and undershoot parameters. These results demonstrate the effectiveness of the proposed MPC-based control in improving the dynamic performance and stability of the Electric Palm Oil Cutter system.

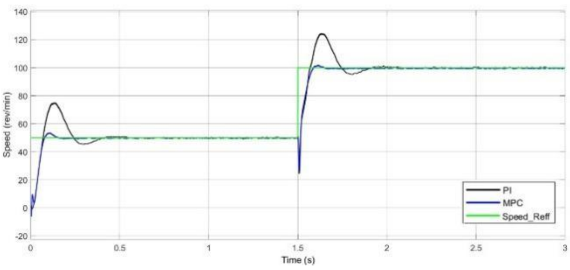

Figure 3. Comparison of dynamic control responses under step-response testing from 50 rev/min to 100 rev/min.

Figure 3. Comparison of dynamic control responses under step-response testing from 50 rev/min to 100 rev/min. At the initial condition between 0 s–1.5 s with a reference setpoint of 50 rev/min, the system with a PI controller exhibits a fast response but with an overshoot of approximately ±25% relative to the reference value. This indicates that although the PI controller provides a high-speed response, its transient stability is relatively poor. Conversely, the MPC controller shows a slightly slower rise time but produces a smoother and more stable response without significant overshoot. This verifies that the predictive strategy implemented in the MPC can effectively anticipate load variations and maintain system stability during transient operations.

Subsequently, when the second setpoint is applied at 1.5 s with a new reference speed of 100 rev/min, the PI controller again exhibits a large overshoot followed by an undershoot immediately after the transition. This behavior indicates oscillation caused by the integral component's delay in adapting to the new condition. In contrast, the MPC controller quickly reaches the steady-state value without significant fluctuations. Based on observation, the system's settling time with the PI controller is approximately 0.5 s longer compared to the MPC, which achieves steady-state in less than 0.25 s. This confirms that MPC has superior convergence capability toward steady-state conditions.

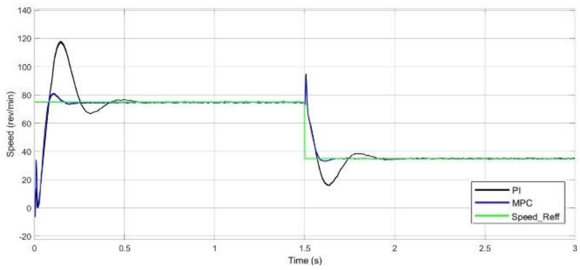

Figure 4. Comparison of dynamic control responses under step-response testing from 75 rev/min to 35 rev/min.

The next test evaluates the system's response to a decreasing reference speed from 75 rev/min to 35 rev/min, as shown in Figure 4. This test aims to assess the controller's capability in handling negative dynamics or deceleration conditions. According to the simulation results, the PI controller again demonstrates a fast response, but with a considerable undershoot before reaching steady-state. This indicates that the PI controller still struggles to maintain stability when the reference value changes abruptly due to the excessive integral effect and delayed error compensation.

Meanwhile, the MPC controller successfully reduces the system speed more smoothly without generating any significant overshoot or undershoot. This indicates that the predictive and optimization process employed in MPC effectively estimates system behavior during sudden changes, thereby producing a more stable and well-controlled transient response. From these results, it can be seen that during deceleration, MPC achieves a faster recovery (settling time) and better stability compared to the PI controller, with a shorter response duration of around 0.15 s.

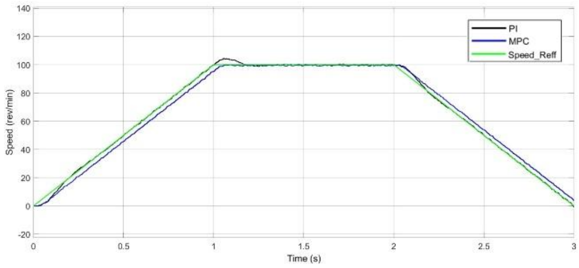

Figure 5. Comparison of system responses under ramp-up and ramp-down testing.

The final test in this study verifies the speed control control system performance under gradual reference variation. In this condition, the responses of both controllers are observed during the ramp-up phase. The PI controller follows the reference signal more closely, showing a faster response but with slight fluctuations at the end of the transient phase. On the other hand, the MPC controller exhibits a small delay during acceleration but produces a much smoother response without overshoot. This demonstrates that the PI controller reacts more aggressively to instantaneous error changes, whereas the MPC optimizes the control action to maintain overall system stability across all predictive stages.

At the steady-state phase of 100 rev/min, the PI controller shows minor oscillations before stabilizing, while the MPC immediately reaches the reference value with a constant and steady response. During the ramp-down phase, similar behavior is observed: the PI controller reacts quickly but with oscillations, whereas the MPC maintains stability with smaller tracking errors. Therefore, the proposed MPC control demonstrates superior performance even in ramp testing, particularly in maintaining response linearity and stability during gradual speed changes. Furthermore, MPC effectively eliminates overshoot and minimizes tracking errors.

Tabel 1. Performance comparison between PI control and MPC control.

Metode	Setting refernece	Settling time (s)	Over shoot (%)	Under shoot (%)
PI	Step response (Step-up)	0.5	25	5
MPC	Step response (Step-up)	0.2	4	-
PI	Step response (Step-down)	0.6	40	5
MPC	Step response (Step-down)	0.25	5	-
PI	Ramp response	-	10	-
MPC	Ramp response	-	-	-

In the steady-state phase at 100 rev/min, the PI controller experiences minor oscillations before stabilizing, while the MPC immediately reaches the reference with a consistent response. During the subsequent ramp-down phase, the same pattern occurs: the PI controller responds quickly but with noticeable fluctuations, whereas the MPC remains stable with minimal tracking errors. Overall, the proposed MPC control method exhibits superior performance across step-up, step-down, and ramp conditions, maintaining smoother transitions and higher steady-state accuracy.

These results clearly demonstrate that the MPC-based speed control system provides better transient stability, faster convergence, and improved robustness, making it highly suitable for MDPMSM control applications implemented in Electric Palm Oil Cutter systems.

4. CONCLUSIONS

This study proposes the use of MPC as a speed control strategy for a encoderless FOC MDPMSM system, which is commonly controlled using a conventional PI controller. Based on simulation verification and analytical results, the MPC technique demonstrates a significant improvement in system performance in terms of dynamic response, stability, and speed tracking accuracy compared to the PI controller.

In the step response test, where the reference speed was suddenly increased from 50 rev/min to 100 rev/min, the PI controller required a settling time of 0.5 s with an overshoot of 25% and an undershoot of 5%. In contrast, the MPC controller successfully reduced the settling time to 0.2 s with only 4% overshoot and no undershoot observed. This represents a 60% faster response and an 84% reduction in overshoot compared to the PI method.

Similarly, in another step response scenario where the speed was decreased from 75 rev/min to 35 rev/min, the PI controller exhibited a settling time of 0.6 s with 40% overshoot and 5% undershoot, while the MPC controller stabilized the system within just 0.25 s with only 5% overshoot and negligible undershoot. These results indicate that MPC can accelerate recovery time by approximately 58% while suppressing transient fluctuations during dynamic conditions.

Moreover, in the ramp response test, the PI controller produced a response that still showed overshoot as it approached the steady-state condition, with deviations up to 10% from the reference speed. In contrast, the MPC controller maintained a more linear and stable tracking performance. This demonstrates MPC's ability to predict and optimize control actions adaptively in response to continuous speed reference variations.

Accordingly, simulation verification confirms that the MPC controller outperforms the PI controller, particularly in terms of response speed, dynamic stability, and reference tracking accuracy. With its capability to anticipate system variations predictively and minimize transient errors, the MPC method proves to be effective and suitable for encoderless MDPMSM speed control systems that require high precision and dynamic response. Furthermore, its application to an electric palm oil cutter system highlights the potential of MPC to enhance control performance, ensuring stable and efficient motor operation under varying load conditions typically encountered in agricultural field environments. In future work, the proposed MPC strategy can be further implemented and validated on FPGA or DSP hardware to evaluate its real-time performance, computational efficiency, and robustness under practical operating conditions, thereby strengthening its feasibility for industrial and agricultural applications.

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