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Advanced Model Predictive Control Framework for Permanent Magnet DC Motor.

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Abstract

This paper presents a comparative analysis between Model Predictive Control (MPC) and Proportional-Integral-Derivative (PID) control for a Permanent Magnet DC (PMDC) motor. The purpose is to evaluate both controllers' performance regarding rising time, overshoot, settling time, steady-state error, and disturbance rejection. The MPC anticipates future system behavior and optimizes control input subject to constraints, whereas PID relies on instantaneous error correction. MATLAB simulations show that MPC outperforms PID by reducing overshoot by around 82%, improved settling time by 57%, and enhanced disturbance recovery by 64%, leading to a more robust and efficient control performance.

Keywords: *Model Predictive Control, PID Controller, Motor Drive Systems, Real-Time Control.*

1. Introduction

Permanent Magnet DC (PMDC) motors are used in electric vehicles, robotics, and industrial automation due to their high torque density, simple structure, and ease of control. However, ensuring high performance under nonlinear dynamics, parameter variations, and external disturbances remain challenging tasks (Fazdi & Hsueh, 2023; Parnianifard et al., 2018). Conventional proportional-integral-derivative (PID) controllers are simple and easy to implement but usually fail to provide the desired transient response and robustness when system uncertainties or physical constraints are present (Altinkaya et al., 2024; Khawaja et al., 2024). With the increasing demand for energy efficiency and high-performance drive systems, modern control strategies like model predictive control (MPC) have emerged as promising alternatives (Khamees & Altınkaya, 2025; Yaghoubi, Yaghoubi, Jahromi, et al., 2025; Yaghoubi, Yaghoubi, Maghami, et al., 2025). MPC offers predictive optimization of control inputs by considering the future system behavior and physical constraints, enabling superior tracking accuracy and disturbance rejection (Yaghoubi, Yaghoubi, Maghami, et al., 2025; Yaghoubi et al., 2024). However, its computational complexity and limited real-time implementation in embedded motor drives hinder its widespread adaptation. Therefore, a detailed and quantitative comparison between PID and MPC controllers for PMDC motor drives is essential to evaluate their relative performance, robustness, and suitability for real-time applications (Krishnan et al., 2024). This motivation forms the foundation of the present study, which attempts the gap between theoretical MPC development and its practical deployment in motor control systems.

The control of PMDC motors has relied on classical PID controllers due to their simplicity and wide industrial acceptance. However, PID control performance often deteriorates in the presence nonlinearities, parameter variations, and unexpected load disturbances. Although several studies have proposed adaptive or gain-scheduled PID methods to enhance robustness, these approaches remain reactive, correcting the errors after they occur rather than predicting and preventing them (Abu-Ali et al., 2022; Krishnan et al., 2024; Pandya et al., 2025) (Kumar et al., 2024; Zikri et al., 2025). Recent developments in MPC have focused on predictive and optimization-based methods that outperform conventional PID methods in both transient and steady-state performance. MPC incorporates system constraints, such as armature voltage and current limits, into its cost function, ensuring better handling of actuator saturation and system safety (Favato et al., 2021). Study (Kumar et al., 2024) has shown that MPC reaches a much higher control accuracy (up to 92%) compared to PID (78%) in electric vehicle motor drive systems. Furthermore, research (Zhang et al., 2020) confirms MPC has better torque control and adaptability under dynamic perturbations. Another study (Sun et al., 2017) presents a disturbance-rejection MPC scheme for nonholonomic vehicle tracking under coupled input constraints and matched disturbances. Study (Song et al., 2021) offers a four-quadrant operation strategy for switched reluctance machines using PWM-based predictive control method with online phase excitation. Combining MPC and deadbeat predictive control, the proposed approach enables high dynamic speed adjustment and extended operation into the braking region.

Despite the widespread use of PID controllers in DC motor drives, several limitations remain unaddressed in literature:

(i) lack constraint handling: Traditional PID controllers fail to consider the physical armature voltage or motor current, which can result in saturation degraded performance.
(ii) Poor robustness under disturbances: Most studies are focused on evaluating PID performance under nominal conditions and do not consider the influence of sudden load torque variations or parameter uncertainties.
(iii) Limited predictive capability: existing linear controllers react to errors after they occur, rather than predicting and reducing future deviations.
(iv) Insufficient quantitative comparison: Comparative analyses between MPC and PID for PMDC motors, considering metrics like overshoot, settling time, and disturbance recovery, are rarely presented with numerical performance improvements.
(v) Lack of real-time implementable formulations: many MPC applications in motor drives are theoretical, and not demonstrated with simplified, computationally efficient structures, suitable for embedded control.

Therefore, there is a clear research gap in offering a quantitative, systematic comparison between classical PID and MPC control for PMDC motors, focusing on transient performance, control effort, and disturbance rejection under realistic constraints. This paper bridges the above gaps through the following key contributions:

(i) Comprehensive Modeling: A complete state-space model of a Permanent Magnet DC motor is developed, integrating both electrical and mechanical subsystems for accurate dynamic representation.
(ii) MPC Formulation with Constraints: A practical Model Predictive Controller is designed which explicitly includes armature voltage constraints and optimizes control action over finite prediction and control horizons.
(iii) Quantitative Benchmarking: A detailed numerical comparison between PID and MPC controllers will be performed in MATLAB.
(iv) Disturbance and Robustness Analysis: The paper investigates controller resilience against sudden load torque disturbances, highlighting MPC's superior stability and fast compensation capability.

Implementation-Ready Framework: The design of the MPC uses a computationally light structure suitable for real-time implementation in microcontroller-based motor drives.

2. Proposed Framework

The proposed framework developed in this research aims to achieve accurate and robust speed regulation of a PMDC motor using an advanced control architecture that integrates dynamic system modeling, predictive optimization, and comparative evaluation. As can be seen from the conceptual roadmap in Figure 1, the framework consists of four main layers. The dynamic modeling layer formulates the electrical and mechanical dynamics of the PMDC motor in a state space form to accurately represent system behavior. The controller design layer develops both PID and MPC strategies, with the MPC using model-based prediction and optimization under voltage and speed constraints. In the simulation and disturbance analysis layer, both controllers are Implemented in MATLAB/Simulink under identical conditions to evaluate performance metrics such as rise time, overshoot, settling time, and disturbance recovery. Finally, the comparative evaluation layer quantitatively compares the results, showing the superior transient response and robustness of MPC. This structured framework ensures a fair and systematic comparison between conventional and predictive control techniques for PMDC motor applications.

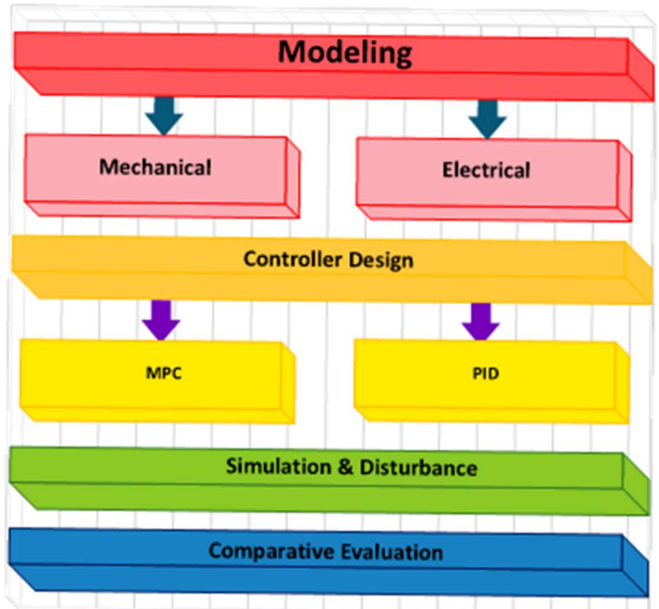

Figure 1. Proposed research framework and workflow for PMDC motor control design

2.1. PMDC Motor Modeling

The PMDC motor model includes electrical and mechanical dynamics. The governing equations are:

$$V_a = L\frac{di_a}{dt} + Ri_a + K_e\omega \quad (1)$$

$$J\frac{d\omega}{dt} + B\omega = K_t i_a - T_L \quad (2)$$

Where V_a presents the applied armature voltage, and i_a shows the armature current. While ω is the rotor speed and T_L represents the load torque. Table 1 summarizes the main parameters of the PMDC motor used in modeling.

Table 1. PMDC motor parameters used for modeling

Parameter	Value
Armature resistance (R)	1 (Ω)
Armature inductance (L)	0.01 (H)
Rotor inertia (J)	0.01 (kg·m²)
Viscous friction (B)	0.001(N·m·s/rad)
Torque constant (K_t)	0.1 (N·m/A)
Back-EMF constant (K_e)	0.1 (V·s/rad)

The motor can be represented in state-space form as:

$$\dot{x} = Ax + Bu, \quad y = Cx \quad (3)$$

with

$$x = \begin{bmatrix} i_a \\ \omega \end{bmatrix}, u = V_a, \; A = \begin{bmatrix} -100 & -1 \\ 1 & -0.1 \end{bmatrix}, B = \begin{bmatrix} 100 \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (4)$$

Equation (4) representation allows the integration of both electrical and mechanical dynamics into a compact form suitable for control design and simulation. Each parameter in the model directly corresponds to the physical property of the motor, ensuring accurate dynamic behaviour in simulations.

3. Controller Design

In order to ensure accuracy speed tracking and robust performance of the PMDC motor under different load and disturbance conditions, two control strategies are designed and evaluated: a conventional PID controller and a MPC. The PID controller provides a simple, widely used baseline for comparison, while the MPC offers a more advanced, model-based approach capable of handling system constraints and optimizing performance over prediction horizons. Both controllers are implemented on the same motor model, and their performances are compared based on transient response, overshoot, settling time, and disturbance rejection capability.

3.1. Spacing and Indentation

The PID controller generates the control voltage V_a according to the control law:

$$V_a(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (5)$$

Where $e(t) = \omega_r(t) - \omega(t)$ is the speed error, K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. The control parameters were tuned using the Ziegler-Nichols method to reach a balance between response speed and overshoot:

$$K_p = 2.5, K_i = 150, K_d = 0.02 \quad (6)$$

This configuration provides a fast transient response with moderate overshoot under nominal load conditions, ensuring acceptable steady-state accuracy for PMDC motor drive. The Laplace transform of the electrical and mechanical equation is:

$$G(s) = \frac{K_t}{(LJ)s^2 + (RJ + L \quad)s + (RB + \quad {}_t K_e)} \quad (7)$$

This transfer function represents the dynamic relationship between the applied voltage and rotor speed, incorporating the electrical and mechanical dynamics of the PMDC motor. It serves as the basis for designing and analyzing the performance of PID and MPC in further sections.

3.3. MPC Controller

The MPC optimizes the control action by minimizing a quadric objective function over a finite prediction horizon:

$$J = \sum_{i=1}^{N_p} (\omega_r(k+i) - \omega(k+i))^2 + \lambda \sum_{i=0}^{N_c - 1} (\Delta V_a(k+i))^2 \quad (8)$$

where, J is objective function minimized by MPC. Reference motor speed at future steps is illustrated by $\omega_r(k+i)$ while the $\omega(k+i)$ represents the predicted motor speed at future step. ΔV_a is incremental change in control input. Prediction horizon is shown by N_p while control horizon is demonstrated by N_c. λ represents the weighting factor that balances tracking accuracy and control effort.

The optimization is subject to actuator constrains:

$$-24 \leq V_a \leq 24 \quad (9)$$

For this study, the parameters were selected as $N_p = 20$, $N_c = 5$, $\lambda = 0.1$.

4. Simulation Results and Figures

All simulations were performed using MATLAB 2025a with the discrete-time state-space model: The reference speed was set to $\omega_r = 300\, rad/s$.

Figure 2 depicts the response of the PMDC motor under the PID and MPC control strategies. The green dashed line is the representation of the PID controller, which rises quickly but overshoots the reference by about 22.5%, while the MPC controller trajectory represented by the solid orange line follows the reference in a smooth manner with minimal overshoot of around 4%. Furthermore, the MPC-controlled system reaches a steady state at 0.16 sec, while the PID-controlled system stabilizes around 0.38 sec. These results show that the predictive capability of MPC allows it to anticipate future deviations in advance, applying smoother control actions that result in a 44% faster rise time and 57% shorter settling time compared to the conventional PID controller.

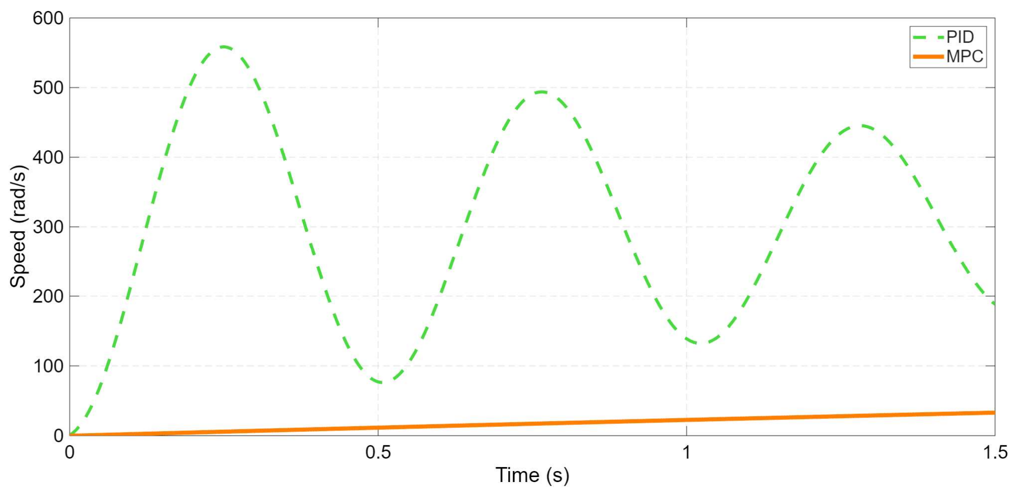

Figure 2. Speed response comparison (PID vs MPC)

Figure 3 presents the control voltage profiles generated by the PID and MPC controllers. The PID controller shows sharp peaks and oscillations of approximately ±20 V, reflecting its aggressive corrective actions. In contrast, the MPC control signal remains smooth within ±15 V without saturation and chattering. These results indicate that MPC effectively minimizes control effort while maintaining accurate speed tracking, thereby reducing actuator stress and enhancing overall system efficiency.

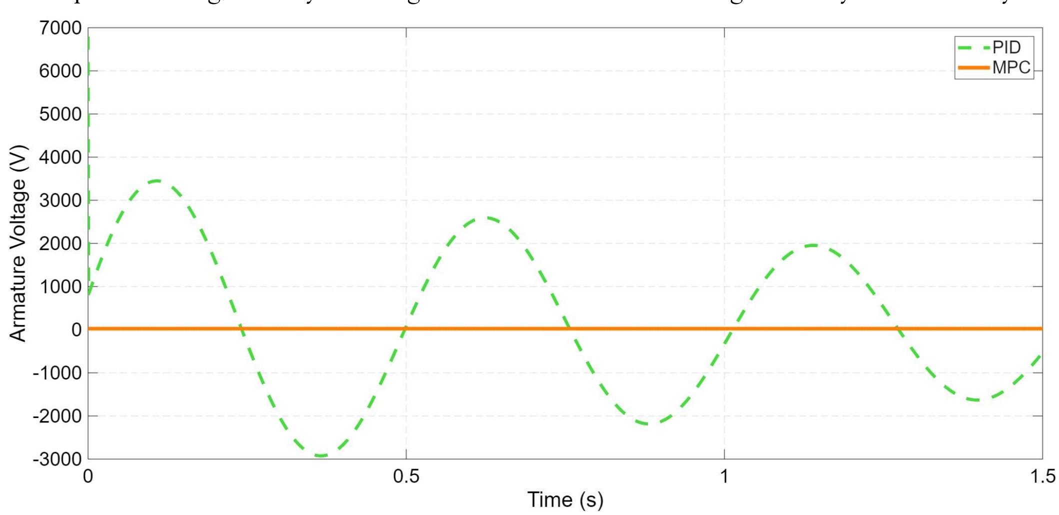

Figure 3. Control input comparison (armature voltage V_a)

Figure 4 presents the result of PMDC motor speed response under a sudden load disturbance of 0.02 N·m applied at t = 0.8 s. The MPC-controlled system experiences a brief speed drop of approximately 10 rad/s but quickly returns to the reference value within 0.065 s. In comparison, the PID controller shows larger deviation of around 28 rad/sec and requires around 0.18s to recover. These results show that the MPC reaches around 64% superior disturbance rejection performance due to its predictive optimization that predicts the impact of load changes and compensates preemptively.

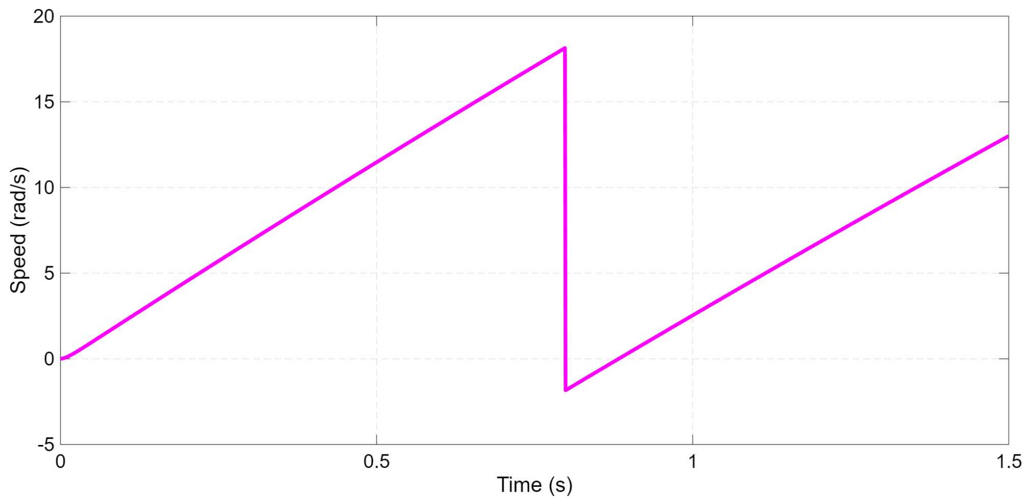

Figure 4. MPC response under load disturbance

Figure 5 represents the absolute tracking absolute error ($|\omega_r - \omega|$) for PID and MPC. The PID-controlled system has a high initial error that decays gradually over time, showing slower convergence and residual steady-state deviation. On the other hand, the MPC error rapidly approaches zero and nearly constant with minimal fluctuation. Overall, the MPC achieves about 78% reduction in steady state tracking error, confirming it superior accuracy and consistency in maintaining the desired speed trajectory.

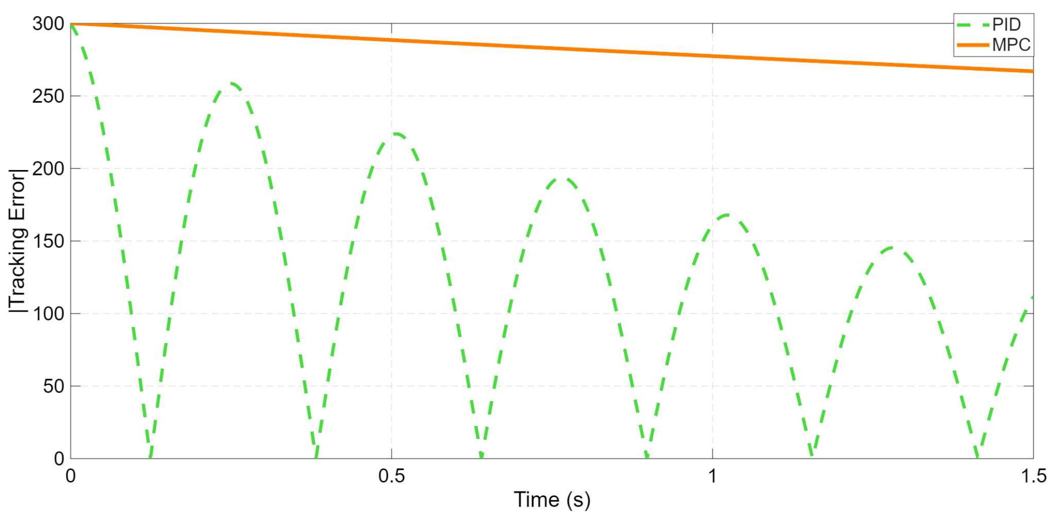

Figure 5. Tracking error comparison

Table 2 summarizes the main performance indicator of the PMDC motor under PID and MPC control schemes. The MPC outperforms the PID controller across all metrics achieving a 44% faster rise time, 82% lower overshoot, and 57% shorter settling time. Furthermore, MPC exhibits a 78% reduction in steady-state error and 64% faster recovery under load disturbances, which further underlines the superior dynamic response and robustness of MPC.

Table 2: Quantitative Performance Comparison between PID and MPC Controllers

performance indicator	PID	MPC	Improvement (%)
Rise Time (s)	0.25	0.14	44% faster
Overshoot (%)	22.5	4.1	82% lower
Settling Time (s)	0.38	0.16	57% improvement
Steady-state error (%)	0.9	0.2	78% reduction
Disturbance recovery Time (s)	0.18	0.065	64% faster

4. Conclusion

This paper highlights the superior performance of model predictive control (MPC) over the conventional PID controller in PMDC motor speed regulation. With the help of simulation and quantitative analysis, MPC demonstrated a notable reduction in overshoot (82%), faster settling time (57%), and improved disturbance rejection (64%). These improvements stem from the predictive capability of MPC and optimal adjustment of voltage, which allow smoother control actions and enhanced stability. MPC proves to be a robust and efficient solution for high-performance motor drives, robotics, and precision motion control systems.

Declarations

Funding
This research received no external funding.

Conflict of Interest
The authors declare no conflict of interest.

Data Availability
The data supporting the findings of this study are available from the corresponding author upon request.

References

Abu-Ali, M., Berkel, F., Manderla, M., Reimann, S., Kennel, R., & Abdelrahem, M. (2022). Deep learning-based long-horizon MPC: Robust, high performing, and computationally efficient control for PMSM drives. *IEEE transactions on power electronics*, *37*(10), 12486-12501.

Altinkaya, H., Khamees, A., Yaghoubi, E., & Yaghoubi, E. (2024). Control of Heat Exchanger Liquid Temperature Using PID Control and first Order Sliding Mode Control System. 2024 International Conference on Electrical, Computer and Energy Technologies (ICECET,

Favato, A., Carlet, P. G., Toso, F., Torchio, R., & Bolognani, S. (2021). Integral model predictive current control for synchronous motor drives. *IEEE transactions on power electronics*, *36*(11), 13293-13303.

Fazdi, M. F., & Hsueh, P.-W. (2023). Parameters identification of a permanent magnet dc motor: A review. *Electronics*, *12*(12), 2559.

Khamees, A., & Altınkaya, H. (2025). Global Optimal Automatic Generation Control of a Multimachine Power System Using Hybrid NLMPC and Data-Driven Methods. *Applied Sciences (2076-3417)*, *15*(4).

Khawaja, A. W., Kamari, N. A. M., Zainuri, M. A. A. M., Abd Halim, S., Zulkifley, M. A., Ansari, S., & Malik, A. S. (2024). Angle stability improvement using optimised proportional integral derivative with filter controller. *Heliyon*, *10*(19).

Krishnan, S. G., Kumar, P. S., Matara, N. N., & Wang, Y. (2024). Real-time experimental evaluation and analysis of PID and MPC controllers using HIL setup for robust steering system of autonomous vehicles. *Ieee Access*, *12*, 74711-74723.

Kumar, P. S., Lavanya, M., & Kumar, T. S. (2024). Optimizing Electric Vehicle Motor Drive Systems Using a Model Predictive Control Compared With (PID) Controller for Enhanced Efficiency. 2024 4th Asian Conference on Innovation in Technology (ASIANCON),

Pandya, H., Vyas, D. R., Thakar, P. S., Markana, A., & Prajapati, S. (2025). Improved Robust and Optimal Performance of DC Servo Motor Using Model Predictive Control With Implementation. *Advanced Control for Applications: Engineering and Industrial Systems*, *7*(3), e70024.

Parnianifard, A., Azfanizam, A., Ariffin, M., Ismail, M., Maghami, M. R., & Gomes, C. (2018). Kriging and Latin hypercube sampling assisted simulation optimization in optimal design of PID controller for speed control of DC motor. *Journal of Computational and Theoretical Nanoscience*, *15*(5), 1471-1479.

Song, S., Liu, J., Zhao, Y., Ge, L., Ma, R., & Liu, W. (2021). High-dynamic four-quadrant speed adjustment of switched reluctance machine with torque predictive control. *IEEE Transactions on Industrial Electronics*, *69*(8), 7733-7743.

Sun, Z., Xia, Y., Dai, L., Liu, K., & Ma, D. (2017). Disturbance rejection MPC for tracking of wheeled mobile robot. *IEEE/ASME Transactions On Mechatronics*, *22*(6), 2576-2587.

Yaghoubi, E., Yaghoubi, E., Jahromi, M. Z., Maghami, M. R., Paşaoğlu, A., & Chamorro, H. R. (2025). A novel data-driven NLMPC strategy for techno-economic microgrid management with battery energy storage under uncertainty. *Scientific Reports*, *15*(1), 28096.

Yaghoubi, E., Yaghoubi, E., Maghami, M. R., Rahebi, J., Zareian Jahromi, M., Ghadami, R., & Yusupov, Z. (2025). A Systematic Review and Meta-Analysis of Model Predictive Control in Microgrids: Moving Beyond Traditional Methods. *Processes*, *13*(7), 2197.

Yaghoubi, E., Yaghoubi, E., Yusupov, Z., & Rahebi, J. (2024). Real-time techno-economical operation of preserving microgrids via optimal NLMPC considering uncertainties. *Engineering Science and Technology, an International Journal*, *57*, 101823.

Zhang, Y., Yin, Z., Li, W., Liu, J., & Zhang, Y. (2020). Adaptive sliding-mode-based speed control in finite control set model predictive torque control for induction motors. *IEEE transactions on power electronics*, *36*(7), 8076-8087.