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COMPARATIVE ANALYSIS OF PROPORTIONAL INTEGRAL DERIVATIVE (PID) AND MODEL PREDICTIVE CONTROL (MPC) CONTROLLERS FOR SHUNT DC MOTOR SPEED REGULATION

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ABSTRACT

Conventional controllers such as Proportional Integral Derivative (PID) are simple and easy to design and implement, but often compromise control quality under varying conditions. In contrast, intelligent controllers offer superior adaptability at the cost of design and tuning complexity. Hence, a comparison is necessary to achieve a suitable trade-off between simplicity and control quality in systems like Direct Current (DC) shunt motor speed control. A shunt DC motor has its field windings connected in parallel (shunt) with the armature windings. This configuration gives the motor numerous advantages, such as ease of control, low armature reaction, quick response and durability, among others. This paper presents a comparison of Model Predictive Control (MPC), PID tuned using Ziegler Nichols, and PID-based Internal Model Control (IMC) approaches for speed control of the shunt DC motor. The controllers are tested through simulation under three distinct input scenarios, namely unit step, variable step, and random integer generator signals. Their performances are evaluated using standard control measures, including Rise Time, Settling Time, Overshoot, Integral of Absolute Error (IAE), and Control Effort. In each case, MPC records the lowest overshoot of 0%, 143% and 15.3% thereby demonstrating greater efficiency by minimizing control effort. However, PID_IMC achieves the lowest IAE, ranging from 0.3 to 12.3 (rad/s) and maintains the fastest settling time of 1.5 seconds, though all the controllers settle at the same time (15 seconds) for the random integer generator input. These results highlight the trade-off between accuracy and robustness: PID_IMC provides better accuracy in terms of tracking error, while MPC ensures robustness, lower overshoot, and reduced actuator demand, making it more suitable for systems operating under unpredictable conditions. The findings aim to assist control engineers in selecting where and when to choose between conventional PID and modern control techniques.

Keywords: Internal Model Control (IMC), Model Predictive Control (MPC), Overshoot; Proportional Integral Derivative (PID), Shunt DC motor.

1.0 INTRODUCTION

PID controller is a classic feedback controller that computes the corrected control signal $u(t)$ as a combination of proportional, integral, and derivative terms of the error e(t). It is one of the famous and widely used conventional controllers, due to its simple and easy design and implementation process, but often compromises control quality under varying conditions. MPC, on the other hand, is an optimization-based control strategy that solves a finite-horizon control problem at each sampling instant, predicting future behavior to minimize a cost function. MPC is known for various advantages that include robustness, disturbance rejection, explicit constraint handling and adaptability despite its complex design and tuning process.

Several attempts were made to enhance the PID performance, such as integrating the controller with the Generic Algorithm (GA) and Fractional Order (FO) into PI/PID [1], [2]. They yielded good results; however, the GA method suffers from slow convergence, while FO-PI/PID requires significant computational resources. FLC and PID (Fuzzy-PID) were also being explored for further enhancement[3], yet the system still faces challenges related to complexity and tuning difficulty. The comparative studies between PID and MPC strategies have largely focused on process control systems such as flow processes[4], Automatic Voltage Regulation (AVR), mass spring damper [5], level (single and double tank) systems[6], and temperature regulation setups[7]. These systems are typically slow responding, single-domain, and exhibit linear or weakly nonlinear behavior, making them less representative of real-world electromechanical systems. Some studies concluded that MPC is superior to PID [5], [7], [8], [9]; however, this may not always be the case.

While many studies have explored DC motor speed control with PID and MPC, very few have directly compared IMC-tuned PID against MPC using the same model and simulation setup[10],[11], [12], [13], [14]. In addition, prior works often use only a narrow set of inputs and focus mainly on output performance specifications (Speed, Overshoot, Settling Time or Rise Time) and overlook how energy related metrics, such as control effort, affect the system performance[4], [5], [15].

This work aims to fill those gaps by testing Ziegler-Nichols-tuned PID, IMC-tuned PID, and MPC on a shunt DC motor under three distinct inputs and assessing both dynamic response and energy related metrics.

1.1 THEORETICAL BACKGROUND

This section highlights the necessary theories and scientific formulas used in conducting the proposed study. To compare the control strategies on Shunt DC motors, its accurate dynamic model is necessary to design. The dynamics are derived from two fundamental subsystems, namely the electrical and mechanical subsystems.

1.2 Electrical dynamics:

This is obtained by applying Kirchhoff’s Voltage Law (KVL) [9] for the armature circuit loop illustrated in Figure 1.

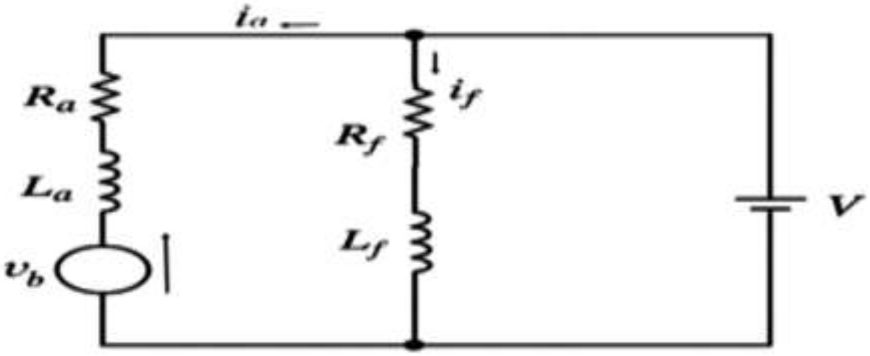

Figure 1: Electrical equivalent of the motor [9].

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + V_b \tag{1}$$

where $V_a,\ i_a, R_a, L_a\ and\ V_b$ are: Armature voltage, Armature current, Armature resistance, Armature inductance and Back EMF (Volt) respectively.

The field voltage equation was omitted because the shunt DC motor operates with a separately excited constant field voltage, which keeps the field current and the magnetic flux constant. The back EMF is proportional to the angular speed of the motor[16] and expressed as:

$$V_b = K_b \omega \tag{2}$$

where $\omega = \frac{d\Theta}{dt}$ is Angular speed (rad/s) and K_b is the Back EMF constant.

1.3 Mechanical dynamics:

This is obtained using Newton's Second Law for Rotational Motion[9]. Figure 2 shows a diagrammatical representation of the dynamics.

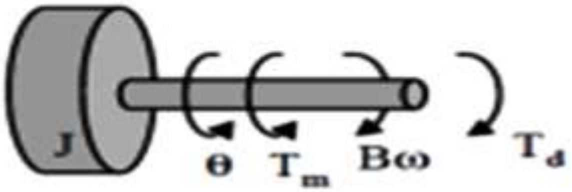

Figure 2: Mechanical dynamics representation [17].

Assuming the system experiences zero load, the sum of forces and torques acting on the motor is [18]:

$$J\frac{d\omega}{dt} + B\omega = T_m \tag{3}$$

where $J, T_d\ and\ B$ are Moment of inertia (kg·m²), Load torque (Nm) and Damping coefficient (Nms), while $T_m = K_t i_a\ is\ \text{Electromagnetic torque (Nm) and} K_t$ is Torque constant [8].

1.4 Transfer Function

After linearizing and taking their Laplace Transform of Equations 1 and 3 (assuming zero initial conditions), we obtain the open-loop transfer function of the motor by dividing the output speed by input voltage[8]:

$$G(s) = \frac{\Omega(s)}{V_a(s)} = \frac{K_t}{(R_a + L_a(s))(Js + B) + K_b K_t} \tag{4}$$

After approximating the physical parameters of the motor, its model was simplified to the following second-order transfer function:

$$G(s) = \frac{2}{s^2\ 12s\ \ 20.02} \tag{5}$$

This continuous time transfer function accurately captures the motor's speed dynamics and was used directly in the PID controller design. For the design of the MPC controller, a discrete time model $G_d(z)$ is required. Thus, the continuous time transfer function $G(s)$ was discretized using Zero Order Hold (ZOH), Equation (6).

$$G_d(z) = Z\left\{\frac{1-e^{-sT_s}}{s}\ G(s)\right\} \tag{6}$$

where Z is transfer model order, T_s=0.1s is sampling time. The discretized model is shown in Equation 7.

$$G_d(z) \ = \frac{0.z^{0}+0.0068.z^{-1}+0.0046.z^{-2}}{1.000-1.1865.z^{-1}+0.3012.z^{-2}} \qquad (7)$$

The PID controller corrects and computes the control signal $u(t)$ as a combination of proportional K_p, integral K_i, and derivative K_d terms of the error e(t) base on equation (7)[19].

$$u(t) = K_p e(t) + K_i \int e(\tau)d\tau + K_d \frac{de(t)}{dt} \qquad (8)$$

1.5 The Process Reaction Curve or First Order Plus Dead Time (FOPDT)

The process reaction curve obtained from the system's step response is characterized by three parameters: the delay time L, the dominant time constant T and the process gain K[12]. Figure 3 shows the motor's step response, while Equation 9 shows the FOPDT model equation.

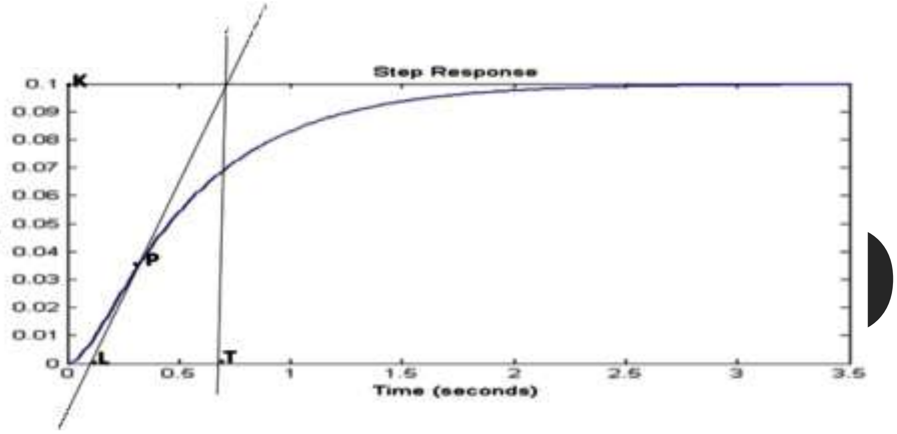

Figure 3. Step response of the motor open-loop plant showing FOPDT parameters [12].

$$G_p(s) = \frac{Ke^{-Ls}}{\tau s+1} \qquad (9)$$

where $\tau \ is \ T$ and $G_p(s)$ is the process transfer function

1.6 Ziegler Nichols

The Ziegler Nichols tuning method uses some predefined formulas for computing the PID controller parameters based on the critical gain(K_u) and critical period (P_u). The formulas are shown in equations (10)[12].

$$K_p = \ 0.6K_u \qquad (10a)$$

$$T_i = 0.5P_u \qquad (10b)$$

$$T_d = \ 0.125P_u \qquad (10c)$$

where $K_i = \frac{K_p}{T_i} \ and \ K_d = K_p * T_i$.

1.7 IMC-based PID

IMC-based PID tuning is model driven approach that calculates PID gains using IMC principles to achieve robust and well damped performance. This approach uses IMC-based PID tuning, predefined formulas derived from FOPDT model [4], and the formulas are given in equations (11).

$$K_p = \frac{\tau}{K(\lambda + L)} \qquad (11a)$$

$$T_i = \tau \qquad (11b)$$

$$T_d = \frac{L\tau}{\lambda+L} \qquad (11c)$$

where λ is the filler and $\tau\ is\ T$.

2.0 METHODOLOGY

This section describes the simulation conditions and procedures used to assess the performance of the controllers. The simulations were performed in MATLAB/Simulink with a sampling time of 0.1 seconds and a total simulation duration of 15.0 seconds to capture both transient and steady-state responses. MATLAB is a high-level language numerical computing and simulation platform. It is widely used in engineering science and mathematics for Modelling, Simulation, Data Analysis and Algorithm Development. It provides built-in tools for control systems and signal processing. Hence, MATLAB is especially useful for designing and analyzing the proposed controllers. However, the Simulink environment enables users to create block diagram models for real-time system simulation and performance evaluation.

The system's continuous transfer function was developed as presented in Equations 4 and 5, which were used for both PID controllers (IMC-based and Ziegler-Nichols), and their gains were computed from their respective tuning formulas shown in Equations 9, 10 and 11. The continuous transfer function was then discretized using Equation 6. The continuous transfer function was used in the MPC design. The entire setup was implemented and tested in MATLAB/Simulink under the three distinct input scenarios mentioned. The time-domain performance and control effort of the controllers were compared and evaluated to determine which control strategy provides superior accuracy, robustness, and efficiency in regulating the speed of the shunt DC motor. Figure 4 illustrates the simulation process flow.

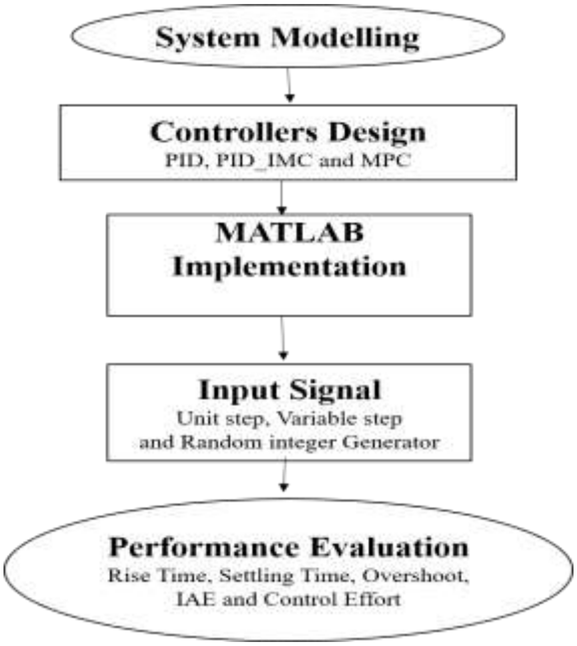

Figure 4: Simulation Flow Chart [7]

The Simulink simulation setup consists of two main configurations: one for the PID controllers and the other for the MPC controller, as shown in Figures 5 and 6.

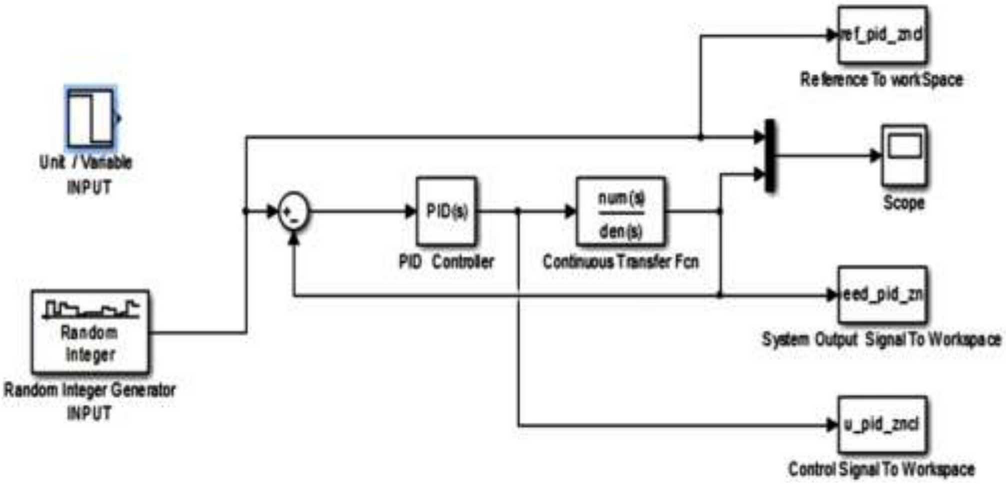

Figure 5: PID model structure. The same PID control structure is used for both PID tuning methods [16]

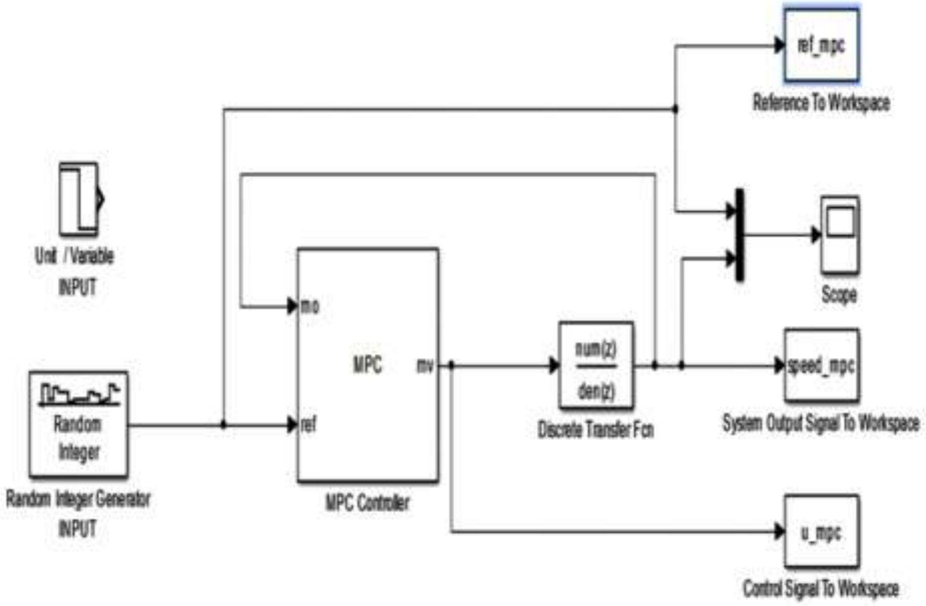

Figure 6: MPC model structure [16]

3.0 RESULTS AND DISCUSSION

This section discusses the controllers' performance results obtained from the simulation and compares them with a result previously obtained by[5].

3.1 Unit Step Response

For the unit step input, the results demonstrate the fundamental differences between the controllers in terms of speed, accuracy, and control smoothness as presented in Table 1. MPC achieved zero overshoot, signifying excellent damping and superior stability. PID_IMC and PID_ZN, on the other hand, exhibited small overshoots (0.74% and 2.15% respectively), showing their aggressive response to step input. Considering how quickly the systems stabilize within a tolerable band, it was shortest for PID_IMC (1.5 s), about 40% faster than PID_ZN and 21% faster than MPC, which implies that PID_IMC offers the most rapid stabilization. Rise time followed the same trend, where PID_IMC reached the reference quickest (1.7 s), reflecting a faster acceleration of motor speed. In terms of IAE, PID_IMC achieved the smallest IAE (0.3037), indicating the most accurate tracking with minimal steady-state error. MPC's higher IAE (0.5654) suggests a slower convergence to the target despite its smooth response. In the case of actuator energy usage, MPC required the least (1422.2), roughly 8% less than PIDs, demonstrating its energy efficiency. Figure 7 shows the controllers' unit step response illustrating the performance metrics graphically.

Table 1: Unit Step Performance Matric

Controller	Overshoot (%)	Settling Time(s)	Rise Time(s)	IAE	Control Effort
PID_ZN	2.1458	2.5	1.9	0.3258	1545.8
PID_IMC	0.7405	1.5	1.7	0.3037	1527.4
MPC	0.0000	1.9	2.0	0.5654	1422.2

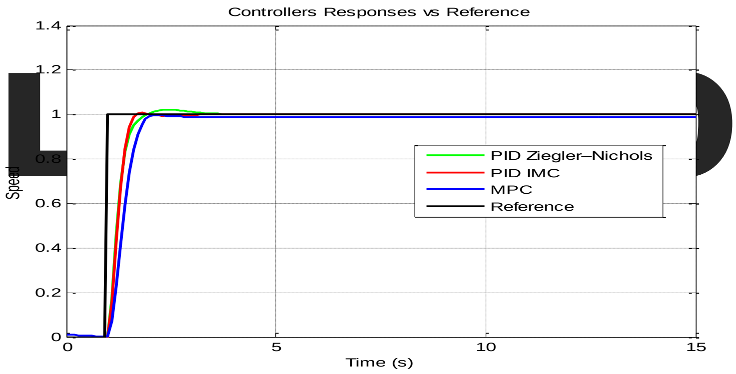

Figure 7: Controllers' Unit Step Responses Comparison

3.2 Variable Step Response

The variable step results are shown in Table 2, where the set point changes abruptly, and the magnitude of parameters shifts dramatically, reflecting how each controller copes with rapid transitions. Overshoot values became very large, exceeding 140% for all controllers, showing that the sudden reference changes push the system beyond its stable limits. Still, MPC achieved the lowest (143.26%), about 5–6% lower than both PID controllers, implying slightly better stability. Settling time was shortest for PID_IMC (1.5 s), meaning it recovered fastest after each new step, while PID_ZN was slowest (2.8 s). The shorter settling time here implies quicker reestablishment of speed after each reference change.

Rise time remained shortest (0.2 s) for both PID controllers, showing faster initial reactions, while MPC's slower rise (0.4 s) indicates a more conservative but smoother behavior. In the case of IAE, PID_IMC is again favored (1.0715), which was about 7% better than PID_ZN and almost 90% better than MPC. A smaller IAE here means more accurate following of the fast-changing reference signal. The Control effort was highest for PID_ZN (2640.9) and lowest for MPC (2153.3), showing that MPC reduced actuator work by 17–19%. Figure 8 shows the controllers' variable step response, illustrating the performance metrics graphically.

Table 2: Variable Step Performance Matric

Controller	Overshoot (%)	Settling Time(s)	Rise Time(s)	IAE	Control Effort
PID_ZN	151.75	2.8	0.2	1.1547	2640.9
PID_IMC	151.85	1.5	0.2	1.0715	2609.9
MPC	143.26	2.4	0.4	2.0108	2153.3

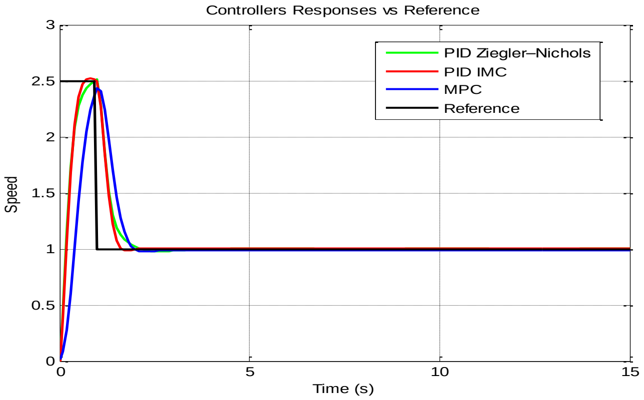

Figure 8: Variable Step Responses Comparison

3.3 Random Integer Generator Response

Random integer performance presented in Table 3, which mimics unpredictable disturbances or stochastic reference signals, the performance parameters reveal how well each controller handles uncertainty. Overshoot remained moderate (15–17%), with MPC again having the least (15.3%), showing slightly better damping and robustness to irregular inputs. Settling time was the same (15 s) for all controllers, meaning each achieved similar long-term stabilization despite noise. Rise time was slowest for MPC (5.5 s), consistent with its conservative adjustment policy, while PID_IMC (5.3 s) and PID_ZN (5.2 s) were marginally faster.

IAE increased sharply for all controllers because random inputs create continuous tracking errors. PID_IMC recorded the lowest IAE (12.288), while MPC's value (24.349) was almost double, indicating it prioritizes stability over strict tracking under unpredictable commands. Control effort was enormous due to continuous changes, but MPC used the least energy (27015), about 30% less than PID controllers, proving it to be the most energy-conscious controller in highly dynamic conditions. Figure 9 shows the controllers' random integer step response, illustrating the performance metrics graphically.

Table 3: Random Variables input Performance Matric

Controller	Overshoot (%)	Settling Time(s)	Rise Time(s)	IAE	Control Effort
PID_ZN	17.343	15	5.2	12.794	39003
PID_IMC	17.541	15	5.3	12.288	37396
MPC	15.308	15	5.5	24.349	27015

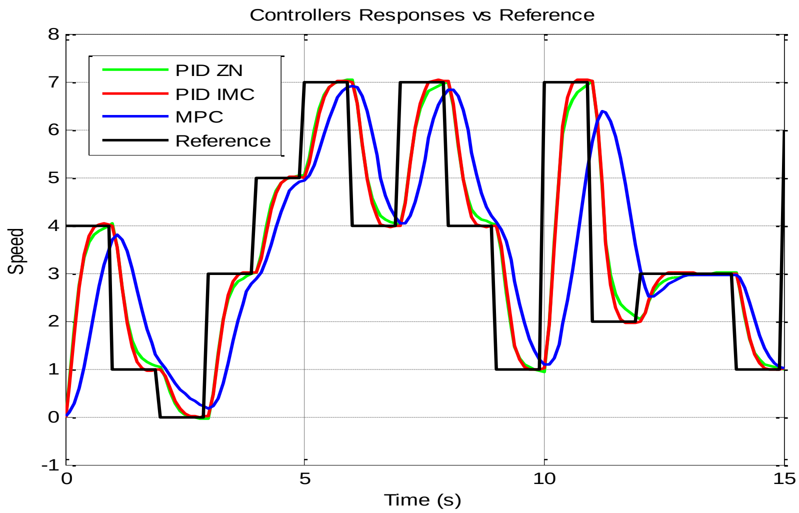

Figure 9: Controllers' Random Integer Generator Responses Comparison

3.4 Result Comparison with Previous Findings

The previous studies mainly tested the controllers under unit step input, for that reason, this work will only consider the unit step response result for comparison.

Table 4: Results Comparison

Performance Metrics	Controllers	This Study	Salem *et al.*,
Overshoot	PID	0.7405	1.58000
	MPC	0.0000	0.0000
Rise Time	PID	1.7	2.4400
	MPC	2.0	1.3745
Settling Time	PID	1.5	4.3500
	MPC	1.9	2.4735
IAE	PID	0.3037	2.3070
	MPC	0.5654	1.2270
Control Effort	PID	1527.4	Not tested
	MPC	1422.2	Not tested
ITAE	PID	Not tested	6.0230
	MPC	Not tested	1.9080

Comparative Discussion of Results

The performance comparison between the present study and that of Salem et al. (2015) in Table 4 provides clear insight into the effectiveness of the IMC-tuned PID and Model Predictive Control (MPC) strategies for DC motor speed regulation. While both studies utilized a unit step input, the present work demonstrates considerable improvement in transient and steady-state performance metrics, highlighting the benefits of model-based controller design. In this study, the IMC-tuned PID achieved an overshoot of 0.74%, while MPC completely eliminated overshoot (0%). In contrast, Salem et al. (2015) reported 1.58% for their optimized PID and 0% for MPC. This represents a 53% reduction in overshoot for the PID controller in the present work. The implication of this reduction is significant—lower overshoot minimizes speed fluctuation above the desired reference.

As for the Times, the IMC-tuned PID settled at 1.5 s compared to 4.35 s reported by Salem et al., showing an impressive 65% improvement. Similarly, the MPC achieved a settling time of 1.9 s, which is 23% faster than the 2.47 s obtained in Salem's work. Shorter settling times indicate faster system stabilization following a disturbance or set point change. The improvement demonstrates the IMC's effective tuning balance between responsiveness and damping. The rise time in this work for IMC-PID is 1.7 s, compared to 2.44 s in Salem's optimized PID, resulting in a 30% faster response. The MPC also shows a rise time of 2.0 s, slightly slower than Salem's 1.37 s, a 46% increase.

A key indicator of steady-state performance, the IAE, was drastically reduced in both controllers in this study. The IMC-PID recorded 0.3037, compared to 2.307 in Salem's PID—a remarkable 87% improvement. Similarly, the MPC achieved 0.5654, compared to 1.227 in Salem's MPC, giving a 54% reduction. Lower IAE values indicate more accurate tracking and less cumulative deviation from the desired speed, reflecting higher steady-state precision and energy efficiency.

Overall, these improvements imply that the controllers developed in this work achieve faster and smoother responses, reduced steady-state error, and enhanced robustness. The IMC-tuned PID provides a strong alternative to conventional optimization-based PID designs by offering both simplicity and model-based adaptability. These results collectively confirm that model-based control strategies—specifically IMC-PID and MPC—offer substantial performance gains in the speed regulation of DC motors, with tangible advantages in energy efficiency, reduced mechanical stress, and smoother operational transients.

4.0 CONCLUSION

This study compared PID controllers tuned using Ziegler–Nichols and IMC methods with a Model Predictive Controller (MPC) for shunt DC motor speed regulation under unit step, variable step, and random input conditions. The analysis considered five performance indices: overshoot, rise time, settling time, IAE, and control effort. The results showed that PID-IMC consistently achieved the fastest and most accurate responses, with a rise time of 0.2 s, settling time 1.5 s, and the lowest IAE across all input types, confirming its suitability for applications requiring quick tracking and minimal steady-state error. MPC, on the other hand, exhibited the smoothest and most stable control behavior, producing zero overshoot, reduced oscillation, and significantly lower control effort up to 35% less energy demand than PID-based methods, highlighting its advantage where actuator efficiency and constraint handling are critical. The Ziegler–Nichols PID, while easy to implement, demonstrated clear limitations, with comparatively higher overshoot and slower stabilization, reinforcing the shortcomings of empirical tuning for precision-sensitive systems. This work provides valuable insights for control engineers and academic researchers in selecting appropriate strategies for DC motor applications and systems of similar dynamics. By quantifying the trade-offs between control speed, accuracy, and energy efficiency, the study establishes a clear understanding of where each controller excels. This comparative assessment thus contributes to improved control strategy selection for not only DC motors but also other industrial systems with similar dynamics. Future work will focus on hybrid control approaches combining PID and MPC principles could be developed to exploit the simplicity of PID and the predictive optimization of MPC.

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