

RESEARCH ARTICLE

Pressure Control based Hybrid MPC and PID Control for Parallel Centrifugal Well Injection Pumps

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Abstract

Well Injection pumps is essential equipment in the upstream oil and gas industry. These pumps are primarily employed to inject water into the reservoir to maintain reservoir pressure, or to waste the water excess after exploration. The most common use Pressure control is only PID control, which has limitations such as Complex and Time-Consuming Parameter Tuning and Poor Adaptability to Parameter Changes. To address this challenge, this study develops hybrid MPC and PID control for pressure control to increase response time and reduce overshoot due to parameter changes. To get the plant model, ARMAX (Auto Regressive Exogenous Moving Average with Exogenous Inputs) is used by analyzing historical measurement data for pressure and throttle valve. The proposed strategy effectively combines the fast response of the PID controller with the foresight and optimization capabilities of the MPC. Load change simulations show that the hybrid MPC-PID controller exhibits faster response time and more precise overshoot reduction capability compared to the single PID and pure MPC strategies. The final optimized model achieved substantial improvements in the IAE index, where the hybrid MPC-PID achieved 0.37% compared to 4.71% for the pure MPC and 7.24% for the PID controller. The implementation of this Control enables increased efficiency in the Water Injection Pump.

Keywords: armax, hybrid mpc-pid, parallel centrifugal injection pump, pressure control, pump efficiency.

I. INTRODUCTION

During oil exploration, one of the excess products of exploration is the water separated from the mixture of oil, water, and gas extracted from underground. This separation process takes place at the Gathering Station (GS). There are two (2) common ways to manage the water resulting from exploration by reinjecting it back into the ground or discharging it into the canals or the rivers. To inject the excess water into the reservoir, well injection pump is used. Therefore, water injection pumps are essential equipment in oil and gas production.

Maintaining the pump discharge pressure requires control of the throttle valve opening on the discharge line, which directly affects the performance and efficiency of the pump. If the throttle valve is opened too wide, then flow rate increases which is causing drop in pump discharge pressure and resulting in rise in motor current which reduces the lifecycles of the motor. Therefore, to mitigate this challenge this study focused on controlling discharge pressure of the pump.

For a long time, simple and easy-to-implement PID controllers have dominated the coordinated control systems [1],[2]. However, when PID faced with the complex, nonlinear, and multivariable coupled control systems, the limitations of PID controllers become clear, making it difficult to achieve the desired control effects [3]. Consequently, academia and industry have been continuously exploring new control strategies, such as MPC gain-scheduling [4], sliding mode control [5], and adaptive control scheme [6]. These advanced control techniques offer greater flexibility and

performance in handling the intricate dynamics and constraints.

Model Predictive Control (MPC) is one of advanced control strategies due to its unique predictive mechanism and ability to handle multivariable coupling and complex constraints [7-9]. It has offered several advantages for managing complex processes with multiple interacting variables and operational constraints. Its predictive capability, combined with constraint handling and optimization, makes it an advanced and practical choice for improving efficiency, reliability, and performance in industrial control applications.

Many academia and industries utilize the application of MPC in the control systems for power plants. J-F Mennemann [10] presented Nonlinear Model Predictive Control of a Variable-Speed Pumped-Storage Power Plant which enables fast closed-loop dynamics while keeping all system constraints, including the pressure constraints along the pipeline system. Zhu et al. [11] developed a three-term MPC strategy and successfully applied it to a 1030 MW supercritical coal power plant. The results show that the MPC significantly improves the performance of pressure control.

However, MPC also has some limitations. Real-time optimization at each step requires significant computational power, making it challenging for fast or embedded systems. The MPC performance heavily depends on accurate system modeling, and any mismatch between the model and the real process can degrade the results. Additionally, the tuning process is complex, involving multiple interacting parameters. Implementing MPC is more demanding than conventional controllers such as PID. It requires system identification,

constraint formulation, and reliable state estimation. Standard MPC also lacks inherent robustness to disturbances and model uncertainties unless extended with robust or adaptive methods.

To address MPC limitations, an innovative model predictive using hybrid MPC and PID control strategy was developed. Some scholars have studied the feasibility of PID–MPC hybrid control. Sanama, Xia, and Nguenpang [12] implemented MPC-PID to enhance the performance of a chiller-fan coil unit. Sen, Singh, and Ramachandran [13] designed a hybrid MPC–PID controller for the Continuous Purification and Processing of Active Pharmaceutical Ingredients. The results show that control loop performance is improved compared to pure PID Controller.

In this study, the application of hybrid MPC and PID is explored for parallel pump pressure control by analyzing historical data. This approach aims to get the optimized pressure control applied to Well injection pumps.

II. SYSTEM DESCRIPTION & MODEL DEVELOPMENT

A. Parallel Pump System

Parallel pump systems are widely used for many applications with high demand of pressure or flow rate. This study utilizes historical data from parallel water injection pumps on existing facility. Figure 1 shows the schematic of parallel well injection pumps to inject the water into the reservoir. P. Wu, Z. Lai, D. Wu, and L. Wang [14] on previous studies shown that the efficient way is to keep each turned-on pump running at the same speed for parallel pump systems consisted of identical pumps. Therefore, in this study, each pump is operated at the same speed.

Three control modes of parallel centrifugal pumps with the same model can be employed: frequency control of motor speed, throttle control, and bypass control [15]. In this study, a combination of Model Predictive Control (MPC) and Proportional-Integral-Derivative (PID) control will be used to regulate the throttle valve.

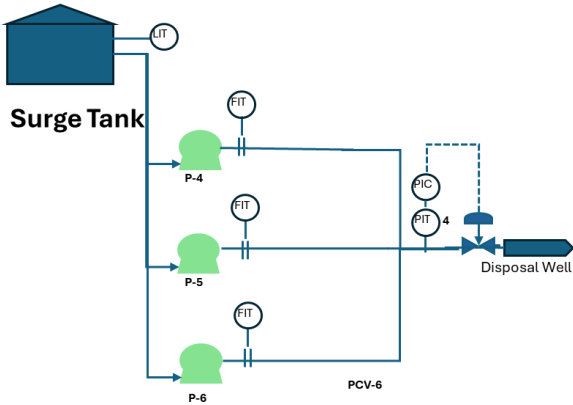


Fig. 1. the schematic of parallel well injection pumps

To develop the simulation, the research methodology is defined as outlined in Fig.2, consists of data collection for input and output system, define input data, output data and sample time, ARMAX model estimation using MATLAB, Convert ARMAX model to transfer function, model validation using another data, design MPC-PID control system in the Simulink MATLAB, tuning PID & MPC parameter and updated control system.

B. Data Collection

A variety of measurement techniques are utilized to gather a comprehensive dataset for analysis. Throttling valve position and pressure indications are recorded during both steady-state and transient operating conditions. Steady-state data is collected once the system has stabilized, ensuring the recorded pressure and throttle valve measurements accurately represent the normal operating conditions. Conversely, transient data is captured during any changes, such as pump startup, shutdown, or valve opening adjustments, to thoroughly characterize the dynamic behavior of the system. All data is acquired with a 1-second sampling rate to provide a detailed record of system performance.

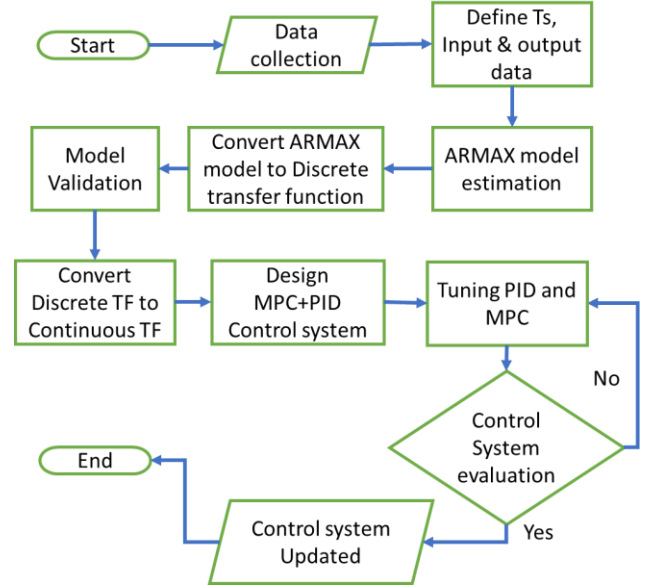


Fig. 2. Flowchart of Methodology for MPC-PID Control system design

C. Define Data

Before ARMAX modeling, the dataset undergoes preprocessing to ensure accuracy and consistency. This stage involves:

- 1) *Data Integration*: Transient data and steady-state data are combined in order to provide a comprehensive representation of the system's performance.
- 2) *Data filtering*: The dataset is examined for inconsistencies or anomalies, which are then removed.
- 3) *define data*: Pressure indication will be used as input data, while throttle valve position will serve as the output data. Ts value will be set as 1 second.

D. ARMAX Model estimation

ARMAX modeling is estimated by collecting synchronized time-series measurements of input signal (valve opening) and system output (pressure) under representative operating conditions. By using MATLAB, the data will be encapsulated in iddata object. The ARMAX model parameters are selected with Suitable polynomial orders as follows: the autoregressive part (na) = 3, the exogenous input part (nb)=2, the moving-average noise part (nc)=1, and the input delay (nk)=0. The AR, X, and MA parameters are simultaneously estimated using the Prediction Error Method by invoking `sys = armax(data,[na nb nc nk])` in MATLAB with the following result:

$$A(z)y(t) = B(z)u(t) + C(z)e(t) \quad (1)$$

Where:

$$A(z) = 1 - 1.061z^{-1} - 0.0768z^{-2} + 0.0164z^{-3} \quad (2)$$

$$B(z) = -22.1 - 22.187 \quad (3)$$

$$C(z) = 1 - 0.2776z^{-1} \quad (4)$$

Based on the above estimation process, the value of Polynomial autoregressive, Polynomial input, Polynomial moving average (A, B, C), noise and input channel correlation (D) and additional dynamic for input (F) are:

$$A : [1 \ -1.0629 \ 0.0768 \ -0.0164] \quad (5)$$

$$B : [-22.1818 \ 22.1712] \quad (6)$$

$$C : [1 \ -0.2776] \quad (7)$$

$$D : 1 \quad (8)$$

$$F : 1 \quad (9)$$

By employing ARMAX estimation, a fit to the estimation data is achieved with value 99.4%. FPE value is 0.6818 and an MSE value is 0.6535. This indicates that a substantial proportion of the dynamics within the estimation data has been successfully captured. The mean squared prediction error value (MSE) of 0.635 suggests a minimal average error per sample. Furthermore, the FPE value is 0.6818, slightly greater than the MSE value, implying that this model has appropriate parameters and does not have redundant parameters.

Based on numerator value (6) and denominator value (5), discrete transfer function can be addressed as below:

$$G(z) = \frac{-22.18z + 22.17}{z^3 - 1.061z^2 - 0.0768z + 0.0164} \quad (10)$$

The negative numerator coefficient (-22.18) in the transfer function typically arises from the inverse relationship between input and output. This negative sign indicates reversed system action. In a valve-pressure system, increasing valve opening can lead to a decrease in output pressure.

E. Model Validation

The residual-correlation diagnostics for ARMAX model (figure 3) indicates that apart from the necessary unity spike at lag 0, all autocorrelation coefficients of the residuals remain within the $\pm 2/\sqrt{N}$ significance bound. Similarly, all cross-correlations between the residuals and the input signal are within these limits. This suggests that the residuals approximate white noise and do not exhibit any residual dependence on the input. This observation indicates the conclusion that the model effectively represents the system's dynamics, leaving no substantial structure or input-driven components unmodeled.

To validate the model, hold-out validation is performed. By using actual data sampling for validation, the model demonstrates excellent performance, achieving a 84.94% fit on the validation set, indicating strong generalization beyond the estimation set. This suggests that the model structure and selected parameter orders effectively capture the underlying system dynamics. approximately 15.06% of variability remaining unexplained under realistic, out-of-sample conditions.

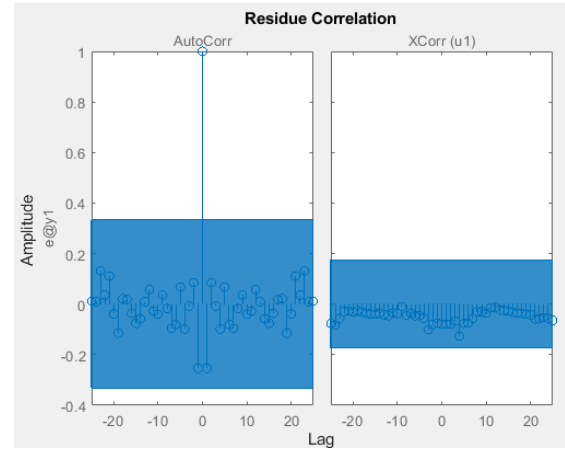


Fig. 3. Residue Correlation graph for Autocorrelation (left panel) and cross correlation with the input u_1 (right panel)

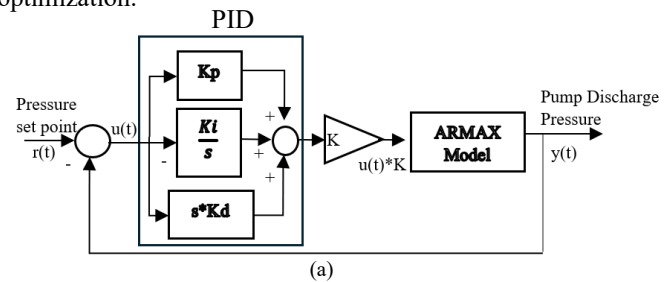
F. Design Strategy of the Control System

Based on section 1, this study introduces a control strategy that integrates the Proportional-Integral-Derivative (PID) and Model Predictive Control (MPC) methodologies. This strategy aims to maintain the performance characteristics of PID control, while simultaneously enabling MPC to optimize a performance metric within a defined prediction horizon, subject to operational constraints on process variables. To leverage the performance of PID control, the MPC controller is configured to send the signal to the PID control signal as an output. Figure 4 compares three pump pressure controllers: a traditional PID loop, a pure MPC scheme with a one-step delay in the feedback path, and a cascaded MPC–PID structure.

The discrete transfer function (10) will be converted to continuous transfer function with the following Tustin's (bilinear) approximation method on MATLAB. This methodology is employed due to its capacity to maintain system stability and ensure a precise correspondence in frequency response between discrete and continuous representations. This characteristic renders it particularly well-suited for control system analysis and design endeavors where accurate dynamic equivalence is paramount. By using sample time (T_s)= 1 second, Continuous transfer function can be address as below:

$$G(s) = \frac{-20.59s^3 + 82.35s^2 + 82.32s - 0.03937}{s^3 + 3.6535s^2 + 3.55s - 0.001857} \quad (11)$$

This third-order transfer function suggests that the system possesses three poles and three zeros, indicating potentially complex dynamic behavior, including oscillations or overshoot. Analyzing these poles and zeros provides insights into the system's stability, transient response, and steady-state accuracy, and helps guide controller design or system optimization.



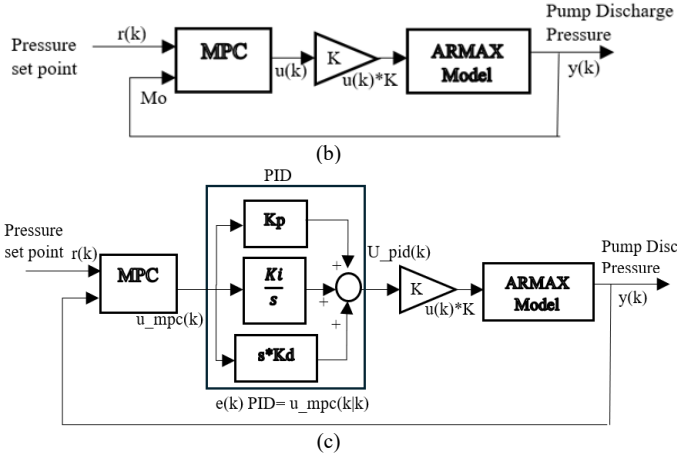


Fig. 4. Simulink Model of Pump Discharge Pressure Control. (a) Traditional PID, (b) Single MPC, (c) Hybrid MPC-PID

Figure 4 compares three control strategies: (a) is a basic PID control loop where the difference between discharge pressure and set-point activates a PID block. The output of the latter, multiplied by a gain factor (K), directly drives the control but without provision for future disturbances or constraints; (b) is a pure MPC which employs an internal model of the plant to calculate optimized control actions over a prediction horizon; (c) is combine them (MPC and PID) in series, which delegate predictive computation to slower timescales while preserving rapid, noise-resistant regulation for immediate adjustments.

In a hybrid MPC-PID structure, the input to the PID controller is typically taken from the first prediction step of the MPC output. $u_{mpc}(k|k)$ represents the control action calculated for the immediate next time step, making it the most relevant for real-time correction. Using this first predicted control ensures that the PID controller responds promptly to changes, maintaining system stability and performance. It reflects the MPC's best estimate of what the system needs at the current moment, based on the latest measurements and reference values. The general formula for a hybrid MPC-PID controller in a cascade configuration is as follows:

$$u_{mpc}(k|k) = r(k) - y(k) \quad (12)$$

Where:

- $u_{mpc}(k|k)$: the MPC control signal at the first prediction step at time k
- $r(k)$ = the reference or setpoint at time k
- $y(k)$ = the actual measured output of the system at time

Then the PID controller computes the control output:

$$u_{pid}(k) = K_p \cdot e(k) + K_i \sum_{i=0}^k e(i) \Delta t + K_d \cdot \frac{e(k) - e(k-1)}{\Delta t} \quad (13)$$

This formula represents the predicted tracking error used by the PID controller, derived from the difference between the current reference and the scaled actual output.

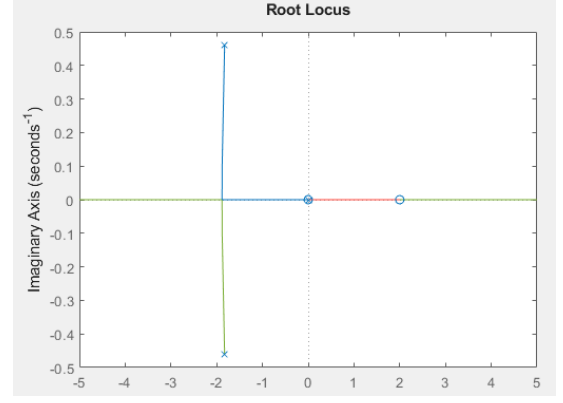


Fig. 5. Root Locus Graph

G. System stability analysis and Gain (K) factor model

Interactive root-locus is performed to find the stability of the system. The Figure 5 shows two open loop poles at approximately $-1.827 \pm j0.46$ and two open loop zeros at $s = -0.0005$ and $s \approx 2$. As the gain K increases from zero, each pole pair traces a semicircular arc inward through the left half plane one branch moving upward from $-1.827 + j0.46$, the other downward from $-1.827 - j0.46$ before terminating at the zero locations on the real axis. Crucially, one of the branches crosses into $\text{Re} > 0$ with the value of 0.0005. This means the closed loop system is unstable. To address the resulting instability, a closed-loop control strategy combining PID and MPC was implemented

By searching at the pole position to the left of the imaginary axis, a gain K of 0.0353 was obtained. Pole position changes to -23.917 , -0.1033 and 0.0048 . This gain (K) factor serves as an external amplification factor and is not part of the original system dynamics to be controlled.

III. SIMULATION RESULTS AND DISCUSSION

In this section, a simulation scenario of a three control (PID, MPC and hybrid MPC-PID) model is developed based on the collected and processed historical data to show the response characteristics for pressure of parallel water injection pump under various operating conditions. The simulation compares the PID control algorithm, MPC control algorithm, and MPC-PID control algorithm.

A. Control system parameter design

Initial PID parameter is calculated before adjusted using Closed-loop characteristic equation. In the process of determining the PID parameters K_p , K_i and K_d , the steady-state gain (K_{ss}) is obtained directly from the plant's transfer function by using dominant pole approximation, excluding the external gain derived from pole placement analysis. The steady-state gain (K_{ss}) reflects the inherent dynamics of the system, which are essential for accurate controller design. In contrast, the gain (K) factor obtained through root locus serves as an external tuning parameter and does not represent the true behavior of the plant. Therefore steady-state gain (K_{ss}) is used for controller design, while gain (K) factor is used for control tuning purposes.

PID parameters K_p , K_i and K_d can be made as below:

$$G(s) = \frac{30.33s^2 + 152.5s - 0.06186}{s^2 + 6.514s - 0.004124} \quad (14)$$

The system transfer function is analyzed to obtain the steady-state gain (K_{ss}) which is calculated by dividing the value at $s = 0$ for the Numerator and Denominator as follows:

$$K_{ss} = \frac{-0.06186}{-0.004124} = 15 \quad (15)$$

By choosing the value of s in the root locus $s = -2 \pm 3j$, can be obtained $\zeta = 0.555$ and $\omega_n = 1/\zeta = 3.605$, then the initial values of K_p , K_i and K_d are obtained as follows:

$$K_p = \frac{2\zeta\omega_n}{K} = \frac{2 \times 0.555 \times 3.605}{15} = 0.267 \quad (16)$$

$$K_i = \frac{\omega_n^2}{K} = \frac{3.605^2}{15} = 0.867 \quad (17)$$

$$K_d = 0 \quad (18)$$

From the calculation above, the initial value of $K_p = 0.267$, $K_i = 0.867$ and $K_d = 0$ was obtained. These values will be tuned to represent a carefully balanced configuration aimed at achieving the desired system performance.

For the pure MPC and hybrid MPC-PID control strategy, the non-optimal MPC parameters were selected as shown in the following table 1 as initial value with the following calculation:

By the original DC gain plant, with $s=0$, $G(0)$:

$$G(0) = \frac{-0.03357}{-0.002238} = 15 \quad (19)$$

By apply the Gain (K) factor = 0.0353

$$K_{dc} = G(0) \times K = 15 \times 0.0353 = 0.5295 \quad (20)$$

This means a unit step in Δu yields about a 0.5295 change in Δy . When the maximum change in control input (Δu_{max}) is equal to 1, then the maximum change in process output (Δy_{max}) is equal to 1 multiplied by the direct-current gain ($1 \times K_{dc}$) which is 0.5295. Therefore, Error weight (W_e) and Control weight (W_u) can be found with the following equation:s

$$W_e = \frac{1}{(\Delta y_{max})^2} = \frac{1}{0.5295^2} = 3.55 \quad (21)$$

$$W_u = \frac{1}{(\Delta u_{max})^2} = \frac{1}{1^2} = 1 \quad (22)$$

These parameters are iteratively refined through simulation in order to achieve an optimal system response by adjusting the Error Weight (W_e) and Control Weight (W_u) values. If the tracking performance is too slow, the Error Weight should be increased; conversely, if the control action is overly aggressive, the Control Weight should be increased.

TABLE 1. LIST OF BASIC DESIGN PARAMETERS

PID		MPC	
K_p	0.26	Prediction Horizon	20
K_i	0.87	Control Horizon	10
K_d	0	Control weight	1
		Error weight	3.55

B. Comparison of PID, MPC, with hybrid MPC-PID

the simulated output on figure 7. In the step-up, the hybrid MPC-PID controller (red) achieves the fastest rise (± 0.8 s to set point). The PID loop (green) takes longer (± 1.2 s rise), has the largest overshoot (± 8 %) and takes nearly 5 s to settle. Conversely, the pure MPC (purple) closely tracks the hybrid's ascent speed while maintaining overshoot below 1 % and settling within approximately 2 s with effectively no residual oscillation. For the downward step, MPC once more has the lowest undershoot (< 1 %) is hybrid MPC_PID and PID is the poorest (± 5 %). All three eliminate steady-state error, but hybrid MPC-PID evidently makes the best overall compromise in terms of speed, low overshoot/undershoot, and fast settling.

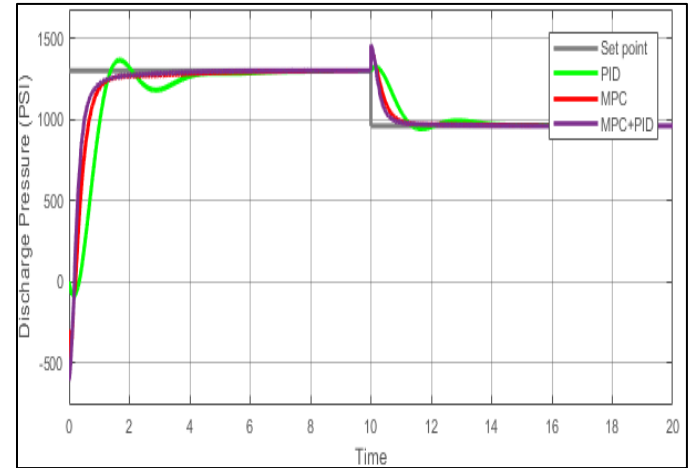


Fig. 5. Pressure control simulation results of PID, MPC and MPC-PID

The simulation also shows the undershoot during initial control, where the output dips below the set point because the controller reacts strongly to a sudden error change, generating a brief corrective impulse that drives the process variable downward. This undershoot is exacerbated if the plant exhibits an inverse-response characteristic, initially responding in the opposite direction of the control effort. The combination of this transient “derivative kick” and the plant’s inverse dynamics causes the output to undershoot before the feedback loop corrects it back to the target. Figure 7 indicates that the MPC control has an inverse response against plants during initial control.

According to Table 2, the hybrid MPC-PID Controller demonstrates a substantial improvement in the Integral Absolute Error Index (IAE), achieving 0.37% compared to 4.71% for the pure MPC and 7.24% for the PID controller.

TABLE 2. PERFORMANCE INDEXES OF DIFFERENCE STRATEGIES

Controller	IAE	%IAE
PID	1636.2	7.24%
MPC	1063.9	4.71%
Hybrid PID+MPC	836.2	0.37%

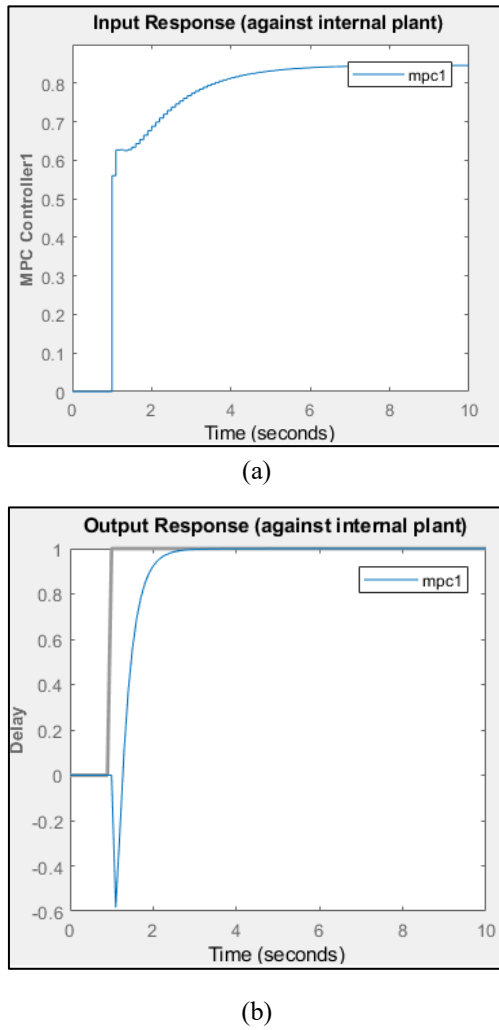


Fig. 7. MPC response against internal plant. (a) Input response, (b) Output response

To reduce overshoot due to zero minimum phase, pre-Filter is utilized. With Pole $z_1 = -23.917$, $z_2 = -0.1033$ and $z_3 = 0.0048$, a pre-filter can be constructed with only the LHP pole as follows:

$$F(S) = \frac{1}{(s+23.917)(s+0.1033)} \quad (23)$$

The LPF is added with $\omega_c = 10$:

$$F(S) = \frac{1}{(s+23.917)(s+0.1033)(\frac{1}{10}s+1)} \quad (24)$$

According to fig 8, the undershoot is significantly reduce during initial response.

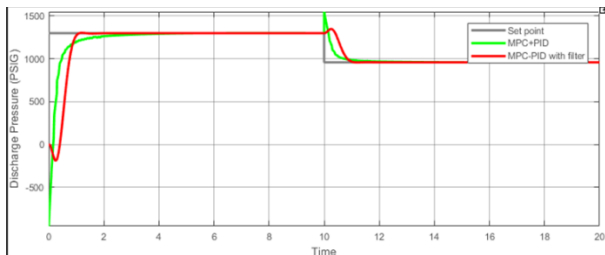


Fig. 8. Signal response after Pre-filter and LPF was added.

Initially, the system exhibited an undershoot of -948.37 without the use of a pre-filter. After implementing the pre-filter, the maximum undershoot was significantly reduced to -121.82 , representing an improvement of approximately 87.15%. During a setpoint change, the maximum overshoot decreased from 1549.1 (without pre-filter) to 1332.0 with the pre-filter, indicating a 14% reduction. However, the inclusion of the pre-filter introduced a slight response delay, with the maximum recorded delay reaching 0.12 seconds.

IV. CONCLUSION

This research successfully developed a pressure control for Parallel Water Injection Pump using hybrid MPC-PID control model. The main conclusions are as follows:

- ARMAX estimation method can effectively estimate a model of dynamic system from historical data with validation performance reaching 95.35%.
- the hybrid PID-MPC controller showed better performance in response speed and tracking accuracy compared to standard PID and pure MPC. The IAE value for the hybrid controller was only 0.37%, much lower than 4.71% for pure MPC and 7.24% for PID. This shows that the hybrid MPC-PID method improves system dynamics and performs close to standard MPC
- zero minimum phase in MPC happened due to a strong reaction to sudden error changes, causing a sharp dip before the system stabilized. To reduce this phenomenon, a pre-filter was utilized, which decreased the undershoot by 87.15% during initial and the overshoot by 15%, though it introduced a response delay of 0.12 seconds.

Future work will aim to enhance the design, reducing undershoot and overshoot phenomenon, and validate the proposed control approach before implementing it in an actual plant.

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