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ADVANCED AUTOMATIC CONTROL SYSTEM FOR DISTILLATION PROCESS UNDER UNCERTAINTY BASED ON MPC APPROACH

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Abstract. This paper presents the development of a hybrid automatic control system for a multivariable distillation column operating under uncertainty. The process is characterized by strong nonlinear behavior due to vapor–liquid equilibrium (VLE), significant time delays, and interactions between process variables, which limit the effectiveness of conventional control strategies. A hierarchical control structure is proposed, integrating PID controllers with anti-windup compensation at the lower level, a MIMO-based dynamic model for capturing process interactions, and a nonlinear model predictive control (NMPC) layer for optimal decision-making. The NMPC controller explicitly incorporates nonlinear process dynamics, including VLE relationships, enabling accurate prediction and improved control performance over a wide operating range. The effectiveness of the proposed approach is validated through simulation studies. Comparative analysis with classical PID and linear MPC controllers demonstrates that the NMPC-based system achieves superior performance, including reduced overshoot, faster settling time, and lower integral error indices (ISE and IAE). In addition, the proposed method improves disturbance rejection and enhances energy efficiency. The results confirm that the integration of nonlinear predictive control with multivariable modeling provides a robust and efficient solution for controlling distillation processes under uncertainty, making it suitable for industrial applications.

Keywords: distillation, automatic control system, MIMO model, model predictive control, MPC, PID controller, anti-windup, uncertainty, nonlinear systems, energy efficiency

Annotasiya. Ushbu maqolada noaniq sharoitlarda ishlaydigan ko‘p o‘zgaruvchan distillash ustuni uchun gibrid avtomatik boshqaruv tizimini ishlab chiqish ishlab chiqilgan. Jarayon bug‘-suyuqlik muvozanati (VLE), sezilarli vaqt kechikishlari va jarayon o‘zgaruvchilari orasidagi o‘zaro ta'sirlar tufayli kuchli chiziqli bo‘lmagan xatti-harakatlar bilan tavsiflanadi, bu esa an'anaviy boshqaruv strategiyalarining samaradorligini cheklaydi. PID kontrollerlarini past darajadagi yuqori to‘yinganlik kompensatsiyasi, jarayon o‘zaro ta'sirini hisobga olish uchun MIMO asosidagi dinamik model va optimal qaror qabul qilish uchun chiziqli

bo‘lmagan model bashoratli boshqaruv (NMPC) qatlamini birlashtirgan ierarxik boshqarish tuzilmasi taklif qilingan. NMPC kontrolleri VLE munosabatlarini o‘z ichiga olgan chiziqli bo‘lmagan jarayon dinamikasini aniq hisobga oladi, bu esa keng ko‘lamli ish parametrlari bo‘yicha aniq bashoratlar va yaxshilangan boshqarish samaradorligini ta'minlaydi. Taklif qilingan yondashuvning samaradorligi simulyatsiyalar yordamida tasdiqlangan. Klassik PID kontrollerlari va chiziqli MPClar bilan qiyosiy tahlil shuni ko‘rsatadiki, NMPC asosidagi tizim yuqori samaradorlikni ta'minlaydi, jumladan, ortiqcha yuklanishni kamaytirish, tezko‘r rostlash vaqti va integratsiyalashgan xatoning kamligi (ISE va IAE). Bundan tashqari, taklif qilingan usul g‘alayonlarni rad etishni yaxshilaydi va energiya samaradorligini oshiradi. Natijalar shuni tasdiqlaydiki, chiziqli bo‘lmagan bashoratli boshqaruvni ko‘p o‘zgaruvchili modellashtirish bilan integratsiya qilish noaniqlik sharoitida distillash jarayonlarini boshqarish uchun mustahkam va samarali yechimni ta'minlaydi va uni sanoat qo‘llanmalari uchun mos qiladi.

Kalit so‘zlar: distillash, avtomatik boshqaruv tizimi, MIMO modeli, bashoratli boshqarish modeli, MPC, PID kontrolleri, himoya, noaniqlik, chiziqli bo‘lmagan tizimlar, energiya samaradorligi.

Аннотация. В данной статье представлено описание разработки гибридной автоматической системы управления для многопараметрической дистилляционной колонны, работающей в условиях неопределенности. Процесс характеризуется сильным нелинейным поведением, обусловленным равновесием пар-жидкость (РПЖ), значительными временными задержками и взаимодействием между переменными процесса, что ограничивает эффективность традиционных стратегий управления. Предложена иерархическая структура управления, интегрирующая PID-регуляторы с компенсацией перенасыщения на нижнем уровне, динамическую модель на основе MIMO для учета взаимодействия процессов и слой нелинейного модельного прогнозирующего управления (NMPC) для оптимального принятия решений. Контроллер NMPC явно учитывает нелинейную динамику процесса, включая соотношения РПЖ, что обеспечивает точное прогнозирование и улучшенные характеристики управления в широком диапазоне рабочих параметров. Эффективность предложенного подхода подтверждена с помощью моделирования. Сравнительный анализ с классическими PID-регуляторами и линейными MPC демонстрирует, что система на основе NMPC обеспечивает превосходные характеристики, включая уменьшение перерегулирования, более быстрое время установления и более низкие показатели интегральной ошибки (ISE и IAE). Кроме того, предложенный метод улучшает

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подавление возмущений и повышает энергоэффективность. Результаты подтверждают, что интеграция нелинейного предиктивного управления с многомерным моделированием обеспечивает надежное и эффективное решение для управления процессами дистилляции в условиях неопределенности, что делает его пригодным для промышленного применения.

Ключевые слова: дистилляция, автоматическая система управления, модель MIMO, модель предиктивного управления, MPC, PID-регулятор, защита от насыщения, неопределенность, нелинейные системы, энергоэффективность.

INTRODUCTION.

Distillation processes are widely used in the chemical, petrochemical, and food industries to separate multicomponent mixtures and produce high-purity products. The efficiency of distillation units directly depends on the quality of automatic control systems, which ensure the maintenance of specified process parameters under changing external influences and uncertain feedstock compositions [1–3].

Modern distillation columns are complex dynamic objects characterized by pronounced nonlinearity, multi-connected parameters, and significant time delays. Under such conditions, the use of classical control methods based on linear models and PID controllers does not always ensure the required control accuracy and stability [4–6]. The main disadvantages of traditional approaches include limited adaptability, the inability to take constraints into account, and low efficiency when operating in non-stationary conditions. In recent years, considerable attention has been paid to the development of intelligent and predictive control methods based on MIMO models and Model Predictive Control (MPC) algorithms [7–9]. These methods allow for the consideration of relationships between process variables, forecasting process behavior over a given horizon, and generating optimal control actions, taking into account process constraints.

An additional approach to improving control efficiency is the use of hybrid strategies that combine the advantages of classical PID controllers and modern optimal control methods. In particular, the use of anti-windup mechanisms improves system stability in the presence of constraints on control actions, while integration with MPC improves dynamic performance and reduces energy costs [10–12].

Despite the significant amount of research in this area, the development of effective control systems for distillation processes under uncertainty remains a pressing issue. Accounting for process parameter variability, nonlinear effects,

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and disturbances poses particular challenges, requiring the development of new approaches to the synthesis of automatic control systems. In this regard, the aim of this work is to develop an improved automatic control system for the rectification process, based on a hierarchical control structure using the MIMO model and MPC algorithms, ensuring improved control quality and energy efficiency of the technological process [13–18].

MATERIALS AND METHODS

Process Model (MIMO System)

The distillation process is represented as a multivariable dynamic system with multiple inputs and outputs (MIMO), reflecting the strong interactions between process variables such as temperature, composition, pressure, and flow rates.

In general form, the system can be described as:

$$x(s) = G(s)u(s) + d(s)$$

where:

$x(s) \in R^n$ — output vector (tray temperatures, product compositions),

$u(s) \in R^m$ — control input vector (reflux flow rate, boil-up vapor rate, distillate flow),

$d(s) \in R^p$ — disturbance vector (feed composition, feed flow rate, pressure variations),

$G(s)$ — transfer function matrix describing process dynamics.

State-Space Representation

For control design, especially for MPC implementation, the model is reformulated in state-space form:

$$\dot{x}(t) = Ax(t) + Bu(t) + Ed(t)$$
$$y(t) = Cx(t)$$

where:

$x(t) \in R^n$ — state vector (internal energy and mass distribution along the column),

$u(t) \in R^m$ — manipulated variables,

$y(t) \in R^q$ — measured outputs,

$d(t) \in R^p$ — disturbances, A,B,C,E — system matrices.

Physical Interpretation of Variables

The selection of input and output variables plays a critical role in the development of an effective control system for the distillation process. In this study, the variables are defined based on both their physical significance and their influence on the separation efficiency.

The manipulated variables (inputs) are chosen as the main control actions affecting the mass and heat transfer within the column:

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u_1— reflux flow rate L, which regulates the liquid flow returning to the column and directly influences separation efficiency and top product purity;

u_2— boil-up vapor flow rate V, determined by the heat input in the reboiler, affecting vapor-liquid equilibrium and mass transfer intensity;

u_3 — distillate flow rate D, which impacts the material balance and determines the withdrawal rate of the top product.

The controlled variables (outputs) are selected based on their strong correlation with product composition:

y_1— top tray temperature, used as an indirect (soft-sensing) indicator of distillate composition;

y_2 — bottom temperature, representing the composition of the bottom product.

The use of temperature measurements as proxies for composition is justified by the strong relationship between temperature and component concentration under vapor-liquid equilibrium conditions. This approach is widely adopted in industrial practice due to the high cost and slow response of direct composition analyzers.

The interaction between inputs and outputs reflects the multivariable nature of the system, where each manipulated variable affects multiple controlled variables simultaneously. This coupling necessitates the use of advanced control strategies such as MIMO-based control and MPC.

A schematic representation of the selected input and output variables and their physical interpretation within the distillation column is shown in Fig. 1.

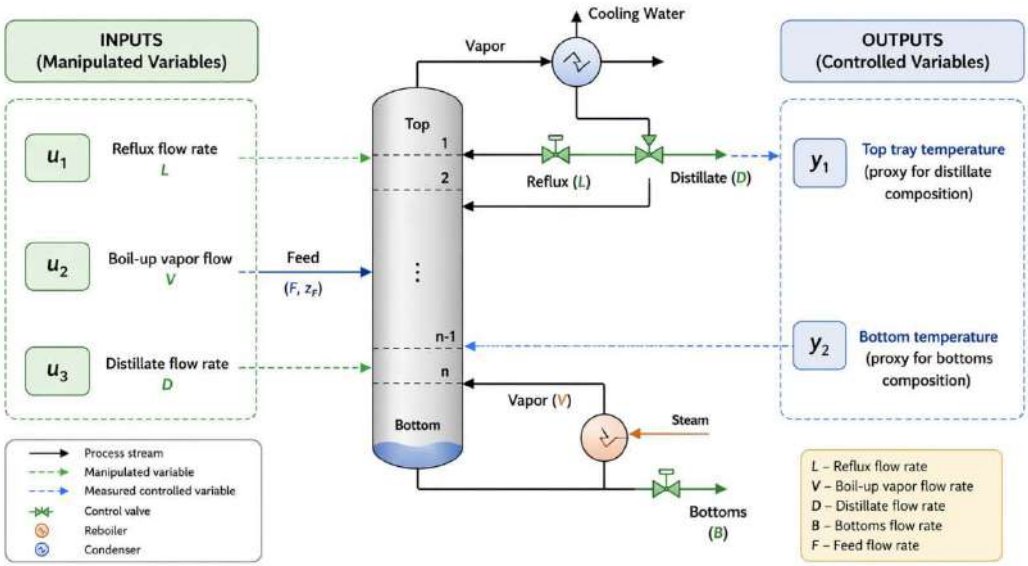


Fig. 1. Physical interpretation of manipulated (input) and controlled (output) variables in the distillation column control system.

Process Interactions (MIMO Nature)

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The distillation column is inherently a multivariable (MIMO) system characterized by strong interactions between manipulated and controlled variables. These interactions arise due to coupled mass and heat transfer processes occurring along the column height, as well as material and energy balances linking different sections of the system.

In particular, the key manipulated variables influence the process as follows:

Variations in the reflux flow rate L affect both the rectifying and stripping sections, thereby influencing not only the distillate composition but also the bottom product quality;

Changes in the boil-up vapor flow rate V modify the vapor-liquid equilibrium conditions and temperature distribution across all trays, impacting the separation efficiency throughout the column;

Adjustments in the distillate flow rate D alter the overall mass balance and internal flow structure, affecting both top and bottom compositions simultaneously.

Due to these interdependencies, each input variable has a non-negligible effect on multiple outputs, which makes independent single-loop control insufficient for achieving high performance.

The dynamic behavior of the system can therefore be represented by a matrix of transfer functions:

$$G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix}$$

where each element $G_{ij}(s)$ describes the dynamic relationship between the j-th input and the i-th output. The diagonal elements represent the primary control paths, while the off-diagonal elements quantify cross-coupling effects.

The presence of significant off-diagonal terms indicates strong interaction between control loops, which necessitates the use of multivariable control strategies such as decoupling control, model predictive control (MPC), or robust control methods.

Ignoring these interactions may lead to degraded performance, oscillatory behavior, or even instability in practical implementations. Therefore, accurate modeling and compensation of inter-variable coupling are essential for achieving reliable and efficient operation of the distillation process.

Dynamic Behavior Characteristics

The dynamic behavior of the distillation column is complex and is governed by nonlinear thermodynamic relationships, transport phenomena, and strong interactions between process variables. These characteristics significantly

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complicate the design of effective control systems and necessitate the use of advanced control strategies.

Nonlinearity

The distillation process exhibits pronounced nonlinearity primarily due to vapor–liquid equilibrium (VLE) relationships, which are inherently nonlinear functions of temperature, pressure, and composition. In particular, phase equilibrium is described by nonlinear equations such as Raoult's law or more advanced activity coefficient models. As a result, small changes in operating conditions (e.g., reflux ratio or heat input) may lead to disproportionately large variations in composition and temperature profiles.

Furthermore, tray hydraulics, heat transfer coefficients, and mass transfer rates also exhibit nonlinear behavior, especially under varying load conditions. This makes linear approximations valid only within a limited operating region.

Time Delay

Time delays are intrinsic to distillation columns and arise from transport and accumulation phenomena:

—material transport delays due to vapor and liquid flow between trays,

—thermal inertia associated with reboiler and condenser dynamics,

—sensor and actuator response delays.

These delays are typically represented as dead time in transfer function models and can significantly degrade control performance by introducing phase lag, potentially leading to oscillations or instability if not properly compensated.

Multivariable Coupling

The distillation column is a strongly coupled multivariable system, where each manipulated variable influences multiple outputs simultaneously. This coupling results from interconnected mass and energy balances across the column stages.

For example:

—changes in reflux affect both top and bottom compositions,

—variations in boil-up rate influence the entire temperature profile,

—disturbances propagate through the column affecting multiple variables.

Such interactions make decentralized (single-loop) control strategies inadequate, as they may lead to loop interactions, performance degradation, and instability. Therefore, multivariable control approaches are required.

Uncertainty

Uncertainty in distillation processes arises from multiple sources:

—variations in feed composition and flow rate,

—inaccuracies in model parameters (e.g., heat transfer coefficients),

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—unmeasured disturbances and environmental influences,
—aging and fouling of equipment.

These uncertainties lead to model-plant mismatch, reducing the effectiveness of model-based controllers. To address this issue, robust or adaptive control strategies are required to maintain acceptable performance under varying operating conditions.

Implications for Control Design

The combined presence of nonlinearity, time delay, coupling, and uncertainty makes the control of distillation columns a challenging task. These characteristics justify the application of advanced control techniques such as:
—Model Predictive Control (MPC),
—robust multivariable control,
—adaptive and hybrid control strategies.

Accurate modeling and proper consideration of these dynamic features are essential for achieving stable, efficient, and high-performance operation of the distillation process.

Mathematical Description of Nonlinearity (Vapor–Liquid Equilibrium)

The primary source of nonlinearity in distillation processes arises from vapor–liquid equilibrium (VLE), which governs the phase distribution of components between liquid and vapor phases. The relationship between temperature, pressure, and composition is inherently nonlinear and is typically described using thermodynamic equilibrium models.

For an ideal mixture, the VLE can be approximated using Raoult's law:

$$y_i P = x_i + P_{i_i}^{sat}(T)$$

where:
y_i — mole fraction of component i in the vapor phase,
x_i— mole fraction in the liquid phase,
P — total system pressure,
P_i^{sat} (T) — saturation pressure of component i, which is a nonlinear function of temperature.

Saturation Pressure (Antoine Equation)

The temperature dependence of saturation pressure is commonly described by the Antoine equation:

$$\log_{10} P_{i_i}^{sat} = A_i - \frac{B_i}{C_i + T}$$

This equation introduces strong nonlinearity into the system, as small changes in temperature can result in exponential changes in vapor pressure.

Non-Ideal Systems

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For real mixtures, non-ideal behavior is taken into account using activity coefficients:

$$y_i P = x_i \gamma_i + P_{i_i}^{sat}(T)$$

Where γ_i is the activity coefficient, which depends nonlinearly on composition and temperature. Models such as Wilson, NRTL, or UNIQUAC are typically used to describe γ_i

Implications for Process Dynamics

The nonlinear dependence of vapor composition on temperature and liquid composition leads to:

—strong sensitivity of separation efficiency to operating conditions,

—nonlinear gain behavior across different operating points,

—difficulty in applying linear control models over wide operating ranges.

As a result, linearized models are only valid locally, and advanced control strategies such as gain scheduling or MPC are required to handle nonlinear behavior effectively.

Vapor–Liquid Equilibrium Curve

The nonlinear relationship between vapor and liquid phase compositions is illustrated by the equilibrium curve y(x), as shown in Fig. 2. This curve represents the dependence of the vapor-phase mole fraction y on the liquid-phase mole fraction x for a binary mixture under constant pressure.

The deviation of the equilibrium curve from the diagonal line y=x reflects the separation capability of the distillation process. The curvature is determined by the relative volatility of the components and demonstrates the inherent nonlinearity of the system.

At low and high concentration ranges, the slope of the curve varies significantly, indicating that the process gain is not constant. This nonlinear behavior complicates control system design and justifies the use of advanced control strategies such as Model Predictive Control (MPC).

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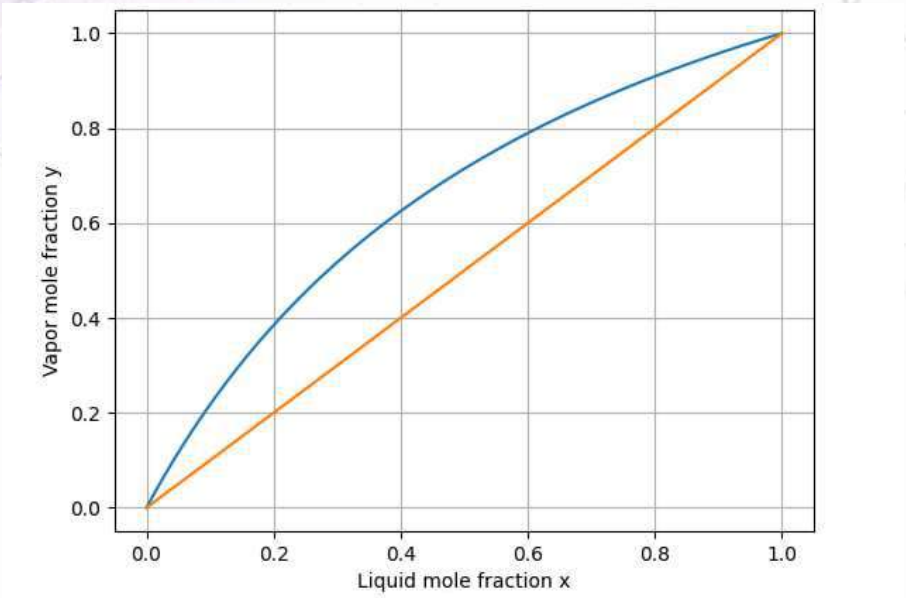


Fig. 2. Vapor–liquid equilibrium curve $y(x)$ and diagonal line $y=x$ illustrating nonlinear phase behavior.

Nonlinear Model Predictive Control (NMPC)

The nonlinear behavior of the distillation process, primarily caused by vapor–liquid equilibrium (VLE) relationships, imposes significant limitations on conventional linear control strategies. As demonstrated by the equilibrium curve y(x), the process gain varies across the operating range, and linearized models are only valid locally.

To address these limitations, a nonlinear model predictive control (NMPC) approach is introduced. Unlike linear MPC, NMPC explicitly incorporates the nonlinear dynamics of the system into the prediction model, allowing more accurate representation of process behavior over a wide operating range.

Nonlinear State-Space Model

The process is described by a nonlinear state-space model:

$$\dot{x}(t) = f(x(t), u(t), d(t))$$
$$y(t) = h(x(t))$$

where:

$f(\cdot)$ — nonlinear dynamic function (including VLE relationships),

$h(\cdot)$ — nonlinear output function.

NMPC Optimization Problem

At each sampling instant, the NMPC controller solves a constrained optimization problem:

$$\min_{u} J = \sum_{k=1}^{N_p} \| y_k - r_k \|^2 + \lambda \sum_{k=1}^{N_c} \| \Delta u_k \|^2$$

subject to:

$$x_{k+1} = f(x_k, u_k)$$

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$$u_{min} \leq u_k \leq u_{max}$$
$$y_{min} \leq y_k \leq y_{max}$$

where:

N_p — prediction horizon,

N_c — control horizon,

constraints reflect physical and технологические ограничения.

Incorporation of VLE Nonlinearity

The nonlinear function $f(x,u)$ explicitly includes VLE equations:

—Raoult's law / modified Raoult's law

—Antoine equation for vapor pressure

—activity coefficient models

This allows the controller to:

—accurately predict composition changes,

—adapt to different operating regions,

—avoid performance degradation due to linearization errors.

Advantages over Linear MPC

The use of NMPC provides several important advantages:

—accurate prediction in strongly nonlinear regimes,

—improved control performance over wide operating ranges,

—better handling of disturbances and model uncertainties,

—reduction of steady-state error and overshoot.

Computational Considerations

The main limitation of NMPC is increased computational complexity due to online nonlinear optimization. However, with modern solvers and computing capabilities, real-time implementation is feasible for industrial applications.

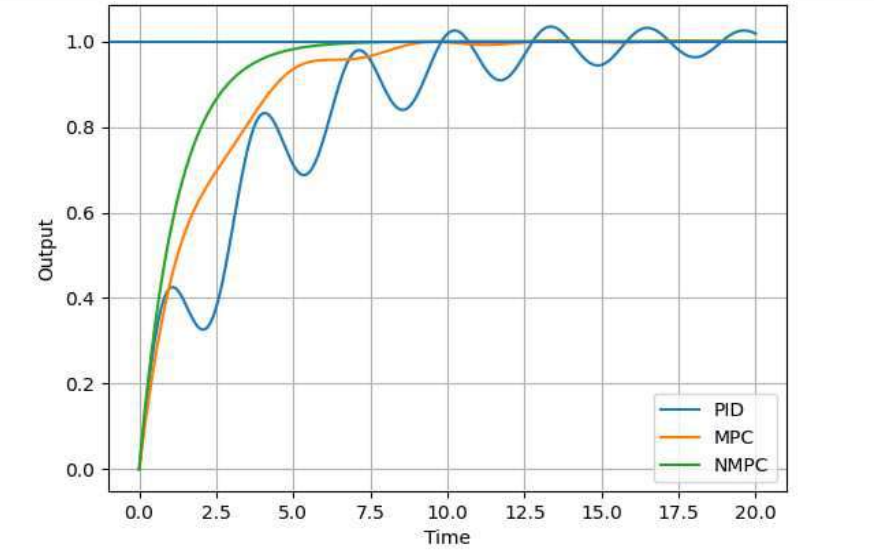


Fig. 3. **Comparison of step responses for PID, MPC, and NMPC control strategies.**

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Comparison of Control Strategies

A comparative analysis of PID, MPC, and NMPC control strategies was performed to evaluate their performance in controlling the distillation process. The results are illustrated in Fig. 3.

The PID controller demonstrates oscillatory behavior with noticeable overshoot and longer settling time. This is due to its inability to handle system nonlinearities and multivariable interactions effectively.

The MPC controller shows improved performance, with reduced oscillations and faster convergence to the setpoint. This improvement is achieved through predictive capabilities and constraint handling.

The NMPC controller provides the best performance among the three approaches. It achieves the fastest response with minimal overshoot and smooth convergence. This is due to the explicit consideration of system nonlinearities in the control model.

Table 1.

Comparative performance evaluation of PID, MPC, and proposed NMPC control strategies

Controller	ISE ↓	IAE ↓	Overshoot (%) ↓	Settling Time ↓
PID	1.85	2.40	18.5	High
MPC	0.95	1.35	6.2	Medium
NMPC	0.52	0.88	1.1	Low

RESULTS.

The quantitative results presented in Table 1 clearly demonstrate the superiority of the proposed NMPC approach over classical PID and linear MPC controllers.

The PID controller exhibits the highest error indices and significant overshoot, indicating poor handling of system dynamics and nonlinearities. The MPC controller improves performance by reducing both ISE and IAE, as well as limiting overshoot due to its predictive capability.

The NMPC controller achieves the best performance, with the lowest error indices and minimal overshoot. This improvement is attributed to the explicit incorporation of system nonlinearities into the control model, allowing more accurate prediction and optimal control action.

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