Enhancing Large-Scale Process Control: Advanced IMC-PI Controller Performance Optimization

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Abstract
This study outlines the development of advanced MIMO (Multiple Input, Multiple Output) configurations, including 2x2, 3x3, and 4x4 systems, utilizing IMC (Internal Model Control) strategies and straightforward decoupling methods. The focal points are the precision of set point tracking and the reduction of control errors, both of which are crucial in control system applications. While the standard IMC PI (Proportional-Integral) controller enhances the servo mechanism of the system, SIMC (Simple Internal Model Control) advances performance in the face of disturbances, a scenario frequently encountered in the field of industrial processes. To maintain stability, the controller gains calculated are adjusted downwards. This approach is compatible with Ziegler-Nichols (Z-N) PI controller tuning parameters, which, while offering a reasonable initial approximation, do not yield the precise system response. Refining the PI controller values based on stability criteria and a detuning factor leads to a more optimized system behavior.

Keywords: PI Controller, MIMO systems, ETF (Extended Transfer Function), EOTF (Enhanced Operational Transfer Function).
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I. INTRODUCTION

MIMO refers to systems where multiple process variables are controlled through numerous inputs. In such systems, different outputs can be influenced by the same inputs due to the inherent complexity of the process. This interdependence within a MIMO system complicates its management. Research has explored the use of IMC and SIMC tuning methods specifically for PI controllers within these multivariable contexts. The IMC tuning method is noted for its prompt response to changes in the setpoint, which is essential for a reliable controller. Alternatively, the SIMC method focuses on improving how well the system can handle disturbances by adjusting the integral time. In developing control systems with multiple loops, concepts such as ETFs (Extended Transfer Functions), EOTFs (Enhanced Operational Transfer Functions), and EOPs (Enhanced Operational Polynomials) have been proposed to address loop interactions. The process begins with breaking down the multi-loop system into single-loop systems to formulate the EOTF. Then, utilizing Ziegler-Nichols tuning, the ETF is transformed into an EOTF, which serves as the basis for decentralized control applications. This research showcases the efficiency of MIMO process simulation technology through three example scenarios, demonstrating the superior performance and stability of a control system designed with a simpler decoupling matrix and an ETF-based controller, compared to more traditional methods.

II. ZIEGLER-NICHOLS TUNING METHOD:

Ziegler-Nichols proposed this method in 1942. This method uses the system's frequency response to calculate PID parameters (critical gain, critical period). The Routh-Hurwitz criteria determine Kcr and Pcr.

Table 1: shows the PID parameter mathematical expressions.

Controller	K_c	T_I	T_D
P	$0.5K_{cr}$	---	0
PI	$0.45K_{cr}$	**0.83**P_{cr}	0
PID	$0.6K_{cr}$	**0.5**P_{cr}	**0.125**P_{cr}

III. EFFECTIVE OPEN-LOOP TRANSFERFUNCTION (EOTF)

Figure 1 depicts two-input, two-output (MIMO) systems that are not centralised.

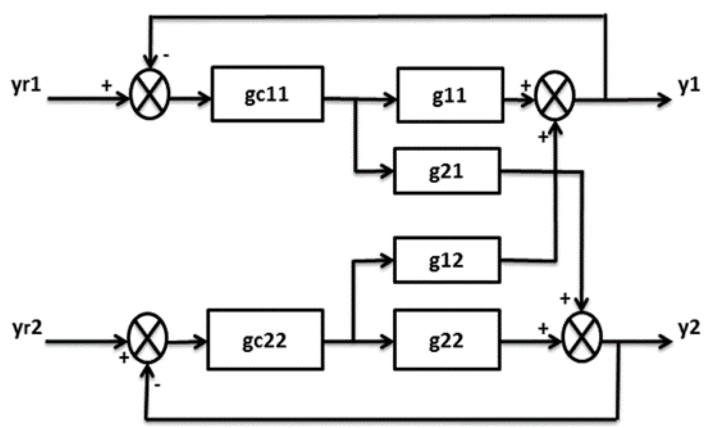

Fig:1 Simple decentralized MIMO process control system

Process transfer function matrices G(s) and G c(s) are used in MIMO systems to describe the distributed control architecture.

$$G(s) = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \quad (1)$$

$$G_c(s) = \begin{bmatrix} G_{11} & 0 \\ 0 & G_{22} \end{bmatrix} \quad (2)$$

It is expressed as First order system with delay time models.

$$G(s) = \frac{K_p}{T_1 s+1} e^{-\theta s} \quad (3)$$

This relationship can be expressed as

$$Y(s) = G(s)U(s) \quad (4)$$

$$Y(s) = \begin{bmatrix} y_1(s) \\ y_1(s) \end{bmatrix} \quad U(s) = \begin{bmatrix} u_1(s) \\ u_1(s) \end{bmatrix} \quad (5)$$

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Vectors of output and input are Y(s) and U(s). This diagram shows the MIMO system's input-output connection.

$y_1(s) = g_{11}(s)\, u_1 + g_{12}(s)\, u_2$ (6)

$y_1(s) = g_{21}(s)\, u_1 + g_{22}(s)\, u_2$ (7)

In MIMO, the input from u I to y I has two routes when the second loop is closed. Effective open-loop dynamics is a term for this. The entire closed-loop transfer function between y1 and u (1) is given by when y 2 = 0.

$\frac{y_1}{u_1} = g_{11} - \frac{g_{12}g_{21}(g_{c2}g_{22})}{g_{22}(1+g_{c2}g_{22})}$ (8)

$\frac{y_2}{u_2} = g_{22} - \frac{g_{21}g_{12}(g_{c1}g_{11})}{g_{11}(1+g_{c1}g_{11})}$ (9)

Effective open-loop transfer functions are listed below (EOTF). It is impossible to directly employ these EOTFs in controller design since they are sophisticated transfer function models. In the creation and reduction of the EOTF model. RGA RNGA and RARTA principles make it simple to obtain the equation for ETF in higher-dimension systems.

IIIA. EQUIVALENT TRANSFER FUNCTION

The normalised gain KN for a certain transfer function, g(s), is defined as follows to represent the dynamic features of a transfer function:

$K_N = \frac{k_1}{\sigma_1} = \frac{k_1}{\tau_1+\theta_1}$ (12)

$\varphi = K_N \otimes K_N^{-T}$ (13)

$\gamma = \frac{\sigma^{\wedge}_1}{\sigma_1} = \frac{\varphi}{\wedge}$ (14)

The parameters of the ETF model may be derived using the RGA and RNGA concepts: (K^, T^ , L^)

K^ = K ⊙ Λ (15)

T^ = Γ ⊗ T (16)

L^ = Γ ⊗ L (17)

The actual Equivalent Open Loop Transfer Function (EOTF) :-g_{11}^{eff} , g_{22}^{eff}

$g_{11}^{eff} = \frac{y_1}{u_1} = g_{11} - \frac{g_{12}g_{21}}{g_{22}}$ (18)

$g_{22}^{eff} = \frac{y_2}{u_1} = g_{22} - \frac{g_{21}g_{12}}{g_{11}}$ (19)

The IMC SIMC tuning rules will improve set-point tracking performance if the pre-requisites are met.

IV. SIMULATION EXAMPLES

IV(A). Vinante and Luyben (VL):

The transfer function matrix: $G(s) = \begin{bmatrix} \frac{-2.2e^{-s}}{7s+1} & \frac{1.3e^{-0.3s}}{7s+1} \\ \frac{-2.8e^{0-1.8s}}{9.5s+1} & \frac{4.3e^{-0.35s}}{9.2s+1} \end{bmatrix}$ (20)

The normalized gain matrix (K_N), RGA(φ), average residence time (T_{ar}), and RARTA (Γ) are calculated as

K^ = K ⊙ Λ

$K^{\wedge} = \begin{bmatrix} -1.3535 & -2.0786 \\ 4.4769 & 2.6455 \end{bmatrix}$ (21)

T^ = Γ ⊗ T

$T^{\wedge} = \begin{bmatrix} 6.6910 & 6.1971 \\ 8.4103 & 8.7940 \end{bmatrix}$ (22)

L^ = Γ ⊗ L

$L^{\wedge} = \begin{bmatrix} 0.9559 & 0.2656 \\ 1.5935 & 0.3345 \end{bmatrix}$ (23)

The actual EOTF model are derived
The first order system :-(Z-N Method)

$$G(s) = \frac{K_p}{T_1 s+1} e^{-\theta s}$$

$$K_p = \frac{T_1}{K_m \lambda}$$

$$\hat{g}^{eff}_{11} = \frac{-1.3535}{6.6910s+1} e^{-0.9559s} \quad (24)$$

$$\hat{g}^{eff}_{22} = \frac{2.6455}{8.7940s+1} e^{-0.3345s} \quad (25)$$

$$K_{p1} = \frac{-6.6910}{1.3535*3*0.9559} = -1.72384$$

$$K_{p2} = \frac{8.7940}{2.6455*3*0.3345} = 3.3125$$

$$T_{I1} = \frac{1}{6.6910} = 0.14945$$

$$T_{I2} = \frac{1}{8.7940} = 0.113713$$

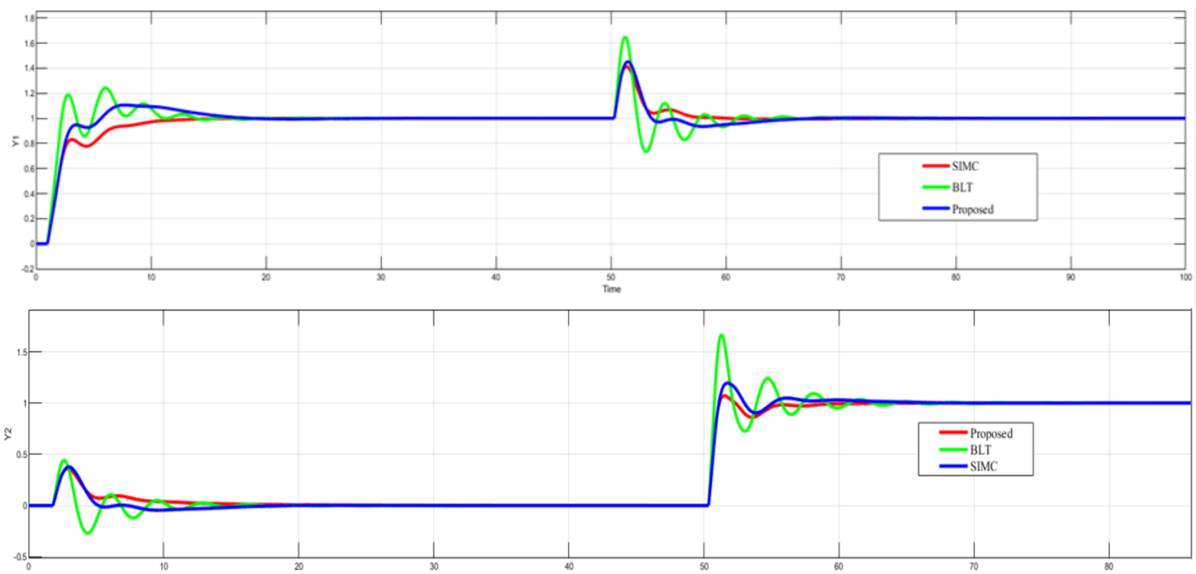

Fig: 2 Closed-loop responses for VL column

Table 2: Output response comparison values

S.No	Process	Method	IAE	ISE
1.	VL	Proposed (IMC)	6.2	2.8
		BLT	7.5	3.1
		SIMC	6.4	2.8

IV CONCLUSION

Enhanced control performance is attainable through the use of an expert system for tuning the PI controller. This system takes into account various factors, including error magnitude, error dynamics, the system's operating point, and aims to optimize integral performance metrics such as IAE (Integral of Absolute Error) or ISE (Integral of Squared Error). Traditional PI tuning methods described in existing literature typically employ static PI parameters, which are not as effective in adapting to setpoint variations or in rejecting disturbances. The IMC PI controller method suggested here addresses these shortcomings. The simulation outcomes and the data presented clearly demonstrate that the IMC PI controller method achieves lower values of IAE and ISE, indicating a superior performance.

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