Development of a Particle Swarm Optimization-Based PI Controller for Temperature Control of a Continuous Stirred Tank Reactor in the Petrochemical Industry

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Abstract- Continuous Stirred Tank Reactors (CSTRs) are important process units in the petrochemical industry, where effective temperature and concentration control is essential for maintaining product quality, process safety, and operational efficiency. The nonlinear characteristics of CSTRs, coupled with process disturbances and variations in operating conditions, can make conventional Proportional-Integral (PI) controller tuning difficult. This paper presents a conceptual development of a Particle Swarm Optimization (PSO)-based PI controller for temperature control of a CSTR. The developed approach combines the simple structure of a PI controller with the optimization capability of PSO to determine suitable proportional and integral gains. The CSTR dynamic is model from material and energy balances, and the controller-design problem is expressed as an optimization problem in which the PI parameters are selected to minimize a transient response function. Performance indices including rise time, settling time, overshoot, where experimented in the controller. Results shows that conventional PI controller have a rise time of 7.2363, settling time of 16.223, and an overshoot of 0. While the PSO-Based PI have a rise time of 1.0689, a settling time of 8.2958 and an overshoot of 4.5456. The results shows that the PSO-Based PI controller have a best performance when compared to the conventional PI controller. The conceptual framework provides a basis for implementation in MATLAB/Simulink and subsequent experimental validation. The developed PSO-Based PI strategy is expected to provide systematic controller tuning and potentially improve transient regulation compared with manually or conventionally tuned PI control. This paper present a practical methodology for evaluating PSO optimization-based PI tuning for nonlinear chemical process applications.

Keywords- CSTR; Particle-Swarm-Optimization; PI-Controller; MATLAB/Simulink

I. INTRODUCTION

Chemical and petrochemical industries require accurate regulation of process variables such as temperature, pressure, concentration, level and flow. The control objective is not only to track desired operating points but also to reject disturbances and maintain safe and economically efficient operation. A major difficulty is that many chemical processes are nonlinear and their dynamic characteristics change with operating conditions. The petrochemical industry relies extensively on chemical reactors for converting raw materials into intermediate and final products. Among the different reactor configurations, the Continuous Stirred Tank Reactor (CSTR) is widely used because of its relatively simple structure and its ability to operate continuously. A typical CSTR involves continuous feed of reactants, mixing within the reactor, chemical reaction, and continuous withdrawal of products. Effective transient control of CSTR is relevant to petrochemical production because deviations in reactor temperature can affect reaction rates, conversion, selectivity, product quality, and equipment safety. An optimized controller can potentially reduce excessive transient excursions and improve tracking of desired operating conditions. The proposed PSO-based PI controller retains the relatively simple PI control structure while introducing an optimization layer for parameter selection. This characteristic can be useful where an existing industrial control system already employs PI control but improved tuning is required. Reactor temperature and concentration must be regulated within appropriate operating ranges to ensure product quality, production efficiency, and safe operation.

CSTR can exhibit nonlinear dynamic behavior resulting from chemical reaction kinetics, heat generation, heat removal, changes in feed conditions, and variations in operating parameters. These characteristics make reactor control a challenging process-control problem. In particular, transient conditions following set-point changes or disturbances may produce overshoot, oscillation, long settling times, or significant deviations from the desired operating point. The conventional proportional-integral (PI) controller is widely adopted in process industries because it provides a useful balance between performance, simplicity and implementation cost. The proportional term produces corrective action proportional to the instantaneous error, while the integral term removes persistent steady-state error. Nevertheless, conventional tuning methods can produce gains that are satisfactory near one operating condition but less effective when the process becomes strongly nonlinear or is subjected to disturbances. Despite its advantages, the performance of a PI controller depends strongly on appropriate selection of K_P andK_i. Conventional tuning approaches can become less satisfactory when the process is nonlinear or when several transient response requirements must be satisfied simultaneously.

Particle Swarm Optimization (PSO) provides the best approach to controller tuning, in which controller gains are treated as particles in a search space, [1]. The particles communicate through their individual and collective best solutions, allowing the algorithm to search for gains that minimize a selected objective function, [2]. This paper will evaluate PI and PSO optimized-Based PI controller.

II. LITERATURE SURVEY

The control of CSTR has received considerable attention because of their nonlinear dynamics and sensitivity to operating conditions. Temperature and concentration dynamics are determined by material and energy balances, while reaction kinetics may introduce strong nonlinearities. Such characteristics can make controller tuning challenging, particularly during transient operating conditions, [3]. Traditional tuning approaches, including Ziegler–Nichols, Cohen–Coon, and trial-and-error methods, may produce considerable overshoot, long settling time, or inadequate robustness when applied to complex processes, [4]. Consequently, optimization-based tuning methods have received considerable attention. The principal advantage of PI control is its ability to achieve zero steady-state error for a step reference in systems where the integral action is appropriate. However, excessive proportional or integral gain may result in oscillation and overshoot, whereas gains that are too small may lead to slow system response. Therefore, [5], assert that controller tuning remains an important consideration in achieving desirable transient and steady-state performance. Chemical processes such as the Continuous Stirred Tank Reactor (CSTR), PI tuning is particularly important because reactor temperature and concentration dynamics can be strongly nonlinear and affected by heat-transfer characteristics, reaction kinetics, disturbances, and changes in operating conditions, [6]. However, optimization techniques is required to provide an alternative to fixed-rule controller tuning, [7]. The PSO as introduced in adaptive control technique is useful in fine-tuning the PI and PID gain to achieve a steady state in the controller. Particle Swarm Optimization was introduced by Kennedy and Eberhart as a population-based optimization algorithm inspired by the collective behavior of natural populations, [8]. The hybrid PSO optimized-based PI controller is one of the adaptive controller technique that have good advantages. However, [9] assert that despite its advantages, PSO-based PI control has some limitations; First, PSO is a stochastic optimization algorithm, meaning that different runs can produce different optimization trajectories. Second, computational requirements may increase as the number of particles and iterations increases. Third, inappropriate selection of PSO parameters can cause premature convergence or slow optimization. Meanwhile, [10], assert that the integration of PSO with PI control can potentially improve transient response and tracking performance while retaining the relatively simple structure of the PI controller. However, the effectiveness of the approach depends on the optimization formulation, PSO parameters, process characteristics, and performance criteria. The review have shown that combining PSO optimized-based PI technique demonstrate best performance and minimized transient occurrence.

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III. CSTR PROCESS MODELING

Figure 1: A simple CSTR Process Modeling

The PSO algorithm operates at the controller design stage to determine appropriate values of $K_P$andK_i. For a first-order exothermic reaction A → B, the concentration balance can generally be represented by

$$\frac{d_{CA}}{dt} = (\frac{F}{V})(C_{Af} - C_A) - K_O \exp[-\frac{E}{RT}]C_A \quad (1)$$

The corresponding energy balance can be written generally as

$$\frac{dT}{dt} = \left(\frac{F}{V}\right)\left(T_f - T\right) + \left(-\frac{\Delta H}{(pC_P)}\right) kO exp\left[-\frac{E}{(RT)}\right] C_A + \frac{Q}{(PC_PV)} \quad (2)$$

$$e(t) = T_{ref} - T_{(t)} \quad (3)$$

$$Q(t) = K_P e(t) + K_i \int e(t)\, dt \quad (4)$$

The nonlinear exothermic CSTR model is used to develop the process plant, where CA is reactor concentration, CAf or C_f is feed concentration, T is reactor temperature, F is volumetric flow rate, V is reactor volume, ρ is density, Cp is heat capacity, T_f is feed temperature, Q is heat addition or removal, ΔH is heat of reaction, k0 is the pre-exponential factor, E is activation energy and R is the gas constant, T_{ref} is the reference temperature, $K_P e(t)$ is the proportional term, $K_i \int e(t)\, dt$ is the integral term. Table 1 shows the experimental value used for simulation.

Table 1: CSTR Simulation Parameters

1. Paramet er	2. Valu e	3. Unit
4. Tref	5. 350	6. K
7. T	8. 300	9. K
10. Tf	11. 300	12. K
13. CAf / CA	14. 1.0 / 1.0	15. mol/ m³
16. ρ	17. 100 0	18. kg/m ³
19. Cp	20. 418 0	21. J/(kg ·K)
22. V	23. 1.0	24. m³
25. F	26. 0.1	27. m³/s
28. k0	29. 7.2× 10¹⁰	30. 1/s
31. E	32. 5.0× 10⁴	33. J/mo l
34. R	35. 8.31 4	36. J/(m ol·K)
37. ΔH	38. −5.0 ×10⁴	39. J/mo l
40. Simulat ion time	41. 60	42. s
43. Step size	44. 0.01	45. s
46. Heater limits	47. 0– 5×10⁵	48. W
49. Conven tional PI Kp / Ki	50. 300 0 / 500	51.

The conventional PI controller is develop as shown. The PI controller consists of proportional and integral components. The proportional term provides an immediate response to the magnitude of the error, while the integral term accumulates the error over time and consequently removes steady-state offset. The PI controller is represented in Laplace domain as;

$$G_c(s) = K_P(S) + \frac{K_i}{S} \quad (5)$$

or

$$G_c(s) = K_P\ (1 + \frac{1}{(T_i S)}) \quad (6)$$

Where Ti = $\frac{K_P}{K_i}$ represents the integral time constant.

PI controller have the ability to achieve zero steady-state error for a step reference in systems where the integral action is appropriate. However, excessive proportional or integral gain may result in oscillation and overshoot, whereas gains that are too small may lead to slow system response. Therefore, controller tuning remains an important consideration in achieving desirable transient and steady-state performance. Similarly, the PSO controller is develop. In PSO, each potential solution is represented by a particle. A group of particles forms a swarm that searches the solution space for an optimum.

For a particle i, its velocity and position are updated according to

vi(k+1) = wvi(k) + c1r1[pbest_i − xi(k)] + c2r2[gbest − xi(k)] (7)

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and

xi(k+1)=xi(k)+vi(k+1) (8)

where vi represents particle velocity, xi represents particle position, pbest_i is the best position previously obtained by particle i, gbest is the best position obtained by the entire swarm, w is the inertia weight, c1 and c2 are acceleration coefficients, and r1 and r2 are random numbers between zero and one. The optimization process continues until a stopping criterion is satisfied, such as a specified number of iterations or achievement of a desired objective-function value. For chemical processes such as the Continuous Stirred Tank Reactor (CSTR), PI tuning is particularly important because reactor temperature and concentration dynamics can be strongly nonlinear and affected by heat-transfer characteristics, reaction kinetics, disturbances, and changes in operating conditions. Consequently, optimization techniques can provide an alternative to fixed-rule controller tuning. In a PSO-based PI controller, the proportional and integral gains are optimized automatically rather than selected solely through conventional tuning rules. The controller parameters can be represented by a particle as

Xi = $[K_P \ K_i]$ (9)

where each particle corresponds to a possible pair of PI gains.

IV. MATLAB/SIMULINK IMPLEMENTATION CONCEPT

The develop controller concept was implemented in MATLAB/Simulink using separate subsystems for the CSTR model, PI controller, PSO optimizer, feedback loop, and performance evaluation.

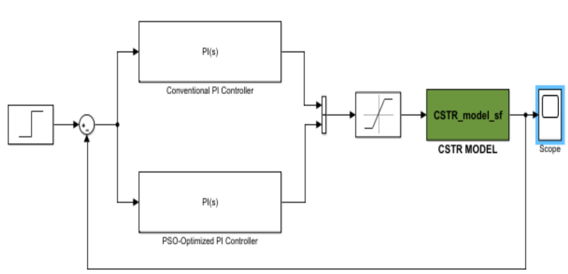

Figure 2: PSO-Based PI Simulink Model

The CSTR subsystem contains the nonlinear material and energy-balance equations. The PI subsystem implements

u(t) = Kp e(t) + Ki ∫e(t)dt. (10)

The PSO algorithm was implemented using MATLAB code that communicates with the Simulink model. During optimization, the algorithm assigns candidate values of Kp and Ki, runs the simulation, obtains the process response, calculates the objective function, and updates the particles.

V. RESULTS ANALYSIS AND DISCUSSION

The results of this paper work is presented for effective analysis and discussion.

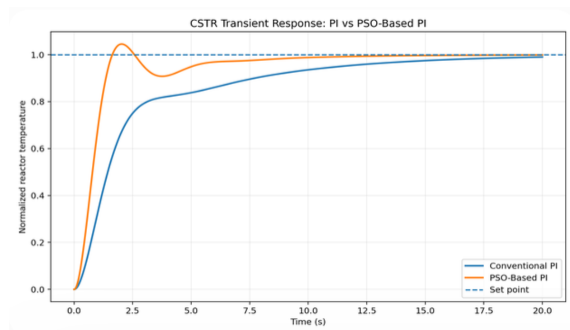

Figure 3: CSTR transient Response for PI and PSO-Based PI Controller

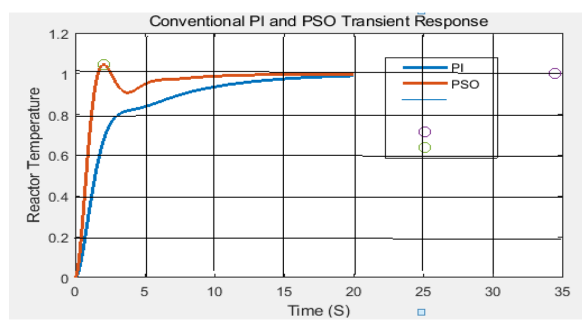

Figure 4: Conventional PI and PSO Transient Response

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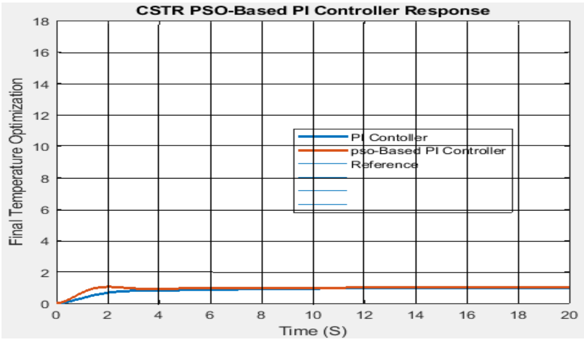

Figure 5: CSTR Temperature Optimization

Table 2: Temperature Transient Performance Results

52. Controller	53. R ise Time	54. S ettling Time	55. O vershoot
56. Co nventional PI	57. 7 .2363	58. 1 6.223	59. 0
60. PS O-Based PI	61. 1 .0689	62. 8 .2958	63. 4. 5456

MATLAB CODE Development

```
Command Window
>> %% CSTR PI versus PSO-Based PI Controller
% Conceptual transient-control model
% Author: Don Basil Nwiwure
>> %.......................................
>> clear;
>> %% Laplace variable
>> s = tf('s');
>> %% Conceptual CSTR linearized plant
>> % Gp(s) = 1/(s^2 + 2s + 1)
>> Gp = 1/(s^2 + 2*s + 1);
>> %%.......................................
>> % CONVENTIONAL PI CONTROLLER
>> %.......................................
>> Kp_PI = 1.20;
>> Ki_PI = 0.35;
>> C_PI = Kp_PI + Ki_PI/s;
>> %% Closed-loop PI system
>> T_PI = feedback(C_PI*Gp,1);
>> %% .......................................
>> % PSO-BASED PI CONTROLLER
>> % .......................................
>> Kp_PSO = 2.80;
>> Ki_PSO = 0.90;
>> C_PSO = Kp_PSO + Ki_PSO/s;
>> %% Closed-loop PSO-PI system
>> T_PSO = feedback(C_PSO*Gp,1);
>> %% Simulation time
>> t = 0:0.01:20;
>> %% Step responses
>> [y_PI,t] = step(T_PI,t);
>> [y_PSO,~] = step(T_PSO,t);
>> %% .......................................
>> % PERFORMANCE PARAMETERS
>> % .......................................
>> Info_PI = stepinfo(T_PI);
>> Info_PSO = stepinfo(T_PSO);
```

VI. DISCUSSION

The results presented have demonstrated that the hybrid technique employ in the CSTR process plant is best for transient temperature optimization. Figure 3 shows the CSTR transient Response for PI and PSO-Based PI Controller, while figure 4 shows the Conventional PI and PSO Transient Response, and figure 5 present the CSTR Temperature Optimization. Whereas, table 2 present the Temperature Transient Performance Results in terms of rise time, settling time and overshoot. Figure 3 to 5 explicitly demonstrate that the conventional PI when excited alone experience high rise time and settling time whereas, PSO-Based PI controller when analyze show a faster rise time of 1.0689 and a settling time of 8.2958 indicating a better response. The conventional PI experience a drawback.

VII. CONCLUSION

This paper presented a conceptual development of a Particle Swarm Optimization-based Proportional-Integral controller for transient control of a Continuous Stirred Tank Reactor in petrochemical-process applications. The develop approach formulates the PI gains as optimization variables and employs PSO to search for controller parameters that minimize a defined transient-performance objective. The CSTR is represented through nonlinear material and energy balances, while performance is assessed using rise time, settling time, overshoot.

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