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Continuous Stir Tank Reactor Plant: A Process Review Perspective

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Abstract – In the realm of chemical processes, the Continuous Stirred Tank Reactor (CSTR) stands as a quintessential industrial apparatus, notable for its dynamic characteristics akin to a second-order nonlinear system. The inherent nonlinear and coupled attributes of CSTR have long been a source of design challenges, particularly in achieving robust control across a broad operating range. The demands of industrial operations necessitate not only precise state estimation but also the ability to swiftly counteract disturbances. In response to this imperative, this paper presents an innovative solution in the form of an event-based sliding mode controller. This novel controller has been meticulously crafted to give resilience to the CSTR system, offering a notable advantage by conserving energy resources. Robustness and efficacy have been at the goal of this design, and through extensive numerical simulations, it was possible to substantiate the controller's ability to withstand parameter variations and rapid shifts in system dynamics. The controller's performance is particularly pronounced in its adept handling of the CSTR's flow rate and temperature, two critical parameters that influence the efficiency and safety of chemical processes. This work marks a significant stride towards enhancing the control and optimization of CSTR systems, with implications that extend beyond chemical processes, underscoring the potential for energy savings and heightened operational stability across various industrial domains.

Keywords – Controller, Stair tanks, process control.

1. Overview of Process Control

Process control is the study and application of automatic control in the field of engineering. The primary objective of process control is to maintain a process at the desired operating conditions, safely and efficiently, while satisfying environmental and product quality requirements (Swapan B., 2023). Proper application of process control can actually improve the safety and profitability of an industrial process, even though rapidly decreasing costs of digital devices and increasing computer speed have enabled high-performance measurement and control systems, it is not an easy task to achieve this because modern plants tend to be difficult to operate due to high complexity and highly integrated process units.

According to Wikipedia project (2019), Automatic process control in technical production process is a combination of control engineering and chemical engineering disciplines which employs industrial control systems to achieve a production level of consistency, economy and safety which could not be achieved purely by human manual control. It is implemented widely in industries such as oil refining, pulp and paper manufacturing, brewery industries, chemical processing and power generating plants. There is a wide range of size, type and complexity, but it enables a small number of operators to manage complex processes to a high degree of consistency. In Caccavale et al. (2016), the author induced that the development of large automatic process control systems was instrumental in enabling the design of large high volume and complex processes, which could not be otherwise economically or safely operated. The applications can range from controlling the temperature and level of a single process vessel, to a complete chemical processing plant with several thousand. Figure 1.1 shows a simple block diagram of process control.

Figure 2.1: simple technical process structure

2. Review of Related Literature

In Nagaraj and Vijakumar (2012), research work on controlled tuning for industrial processes using software computing approach. The work defined the non-linearity of the CSTR as a dynamic process and employed the PID for the controller structure using the software tuning technique. The result was better than the conventional PID. However, the technique is not automated, and requires technical skills to tune the PID using the proposed methods.

Piyush (2016) presented a work on the modeling and control of CSTR using model based neural network predictive control. The work modeled a non linear system as a dynamic process and a neural network model to predict the behavior of the future plants but the challenge of this work is the training algorithm. The neural network employs a feedback propagation algorithm which is complex and do not produce the desired reference control model.

R M, Ganesh. (2016)researched on the implementation and comparative analysis of PID controller and their auto tuning method considering uncertainty for the robust control of the concentration in CSTR. The work compared various controller tuning methods such as the manual tuning method, software tuning method, neuro tuning method and manual tuning method. From the comparative analysis it was observed that the controller all performs best at one area and has limitation on the other. The areas considered for the comparison includes response time, steady state, dead zone performance, stability among others. It was observed and concluded from the work that for a complete control of a cstr plant, combination of controllers will produce the most effective result.

In Colantonio (2015), a method based on state coordinate transformation has been studied for linear input state behavior. Observer based designs for state measurements have been discussed in to name a few. While the method in aforementioned studies ensured asymptotic stability, the effects of disturbance was overlooked and the design failed to deliver desired response under varying process conditions.

In (Agalya and Nagaraj, 2013), the design of a nonlinear feedback controller is analyzed for concentration control of continuous stirred tank reactors (CSTR) which have strong nonlinearities. Continuous Stirred Tank Reactor (CSTR) is one of the common reactors in chemical process and all industrial process requires a solution of specific chemical strength of chemicals considered for analysis. Here they employed the Particle Swarm Optimization (PSO) algorithm based PID controller tuning attempted for the concentration control of Continuous Stirred tank reactor (CSTR). The Integral Square Error (ISE) criterion was used to guide the PSO algorithm to search the controller parameters like Kp, Ki, Kd. A comprehensive simulation is carried out with PID and I-PD controller Structures. The simulation results shows that the PSO based PID controller tuning approach provides better

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performance compared to other conventional PID tuning methods, However the controller response time to non linearity was delayed with our 15 seconds which is not good and cannot be relied upon.

Singha and Mishra (2018) worked on the temperature regulation in a continuous stirred tank reactor using even triggered sliding mode control technique. The work presented a dynamic even triggering rule to maintain the desired performance with minimum computational cost. However the technique has a very low response time to non linearity and despite the controlled technique, the cstr never attain complete stability.

3. Methodology

In this work, an existing continuous stir tank reactor (CSTR) plant was characterised, considering the controller performance at various operating conditions. Then mathematical representations of the Laplace transfer function, auto regressive models, polynomials and estimation model, state space model, input disturbance mode, dynamic plant model and the controller structures were defined. Using the Simulink tool box, the controller was designed to control the flow rate and temperature of the continuous stirred tank reactor.

3.1 Characterization

This thesis characterizes a continuous stirred tank reactor employed in the Cadbury Nigeria PLC for chocolate production. The stirred tank is developed to mix crushed cocoa from tank 1 and other mixed products from tank 2. The storage tank is used to mix the raw material in the appropriate proportion at the desired temperature and concentration. The industrial processing architecture is presented in figure 3.1, with Micrologix 1000 (ALLEN BRADLEY) programmable logic control (PLC) system.

The plant is analyzed using the PLC via an RSLogix 500 software package designed to monitor the operability of PLC online or offline. Other hardware components in the setup process plant includes switched power supply (24V), sub-mersible pump, level sensor, silence alarm, push button, cut off sensor, indicator and relays. The PLC specification is presented in table 3.1;

Table 3.1: Specification of the PLC

Parameters	**Values**
Memory size	1K EEPRO
Power supply voltage	20.4 -26.4 V DC
Power supply Max	Inrush current 30A for 8ms
Operating Temperature	Horizontal mounting 0°C to + 55°C
Storage temperature	-40°C to +85°C
Operating humidity	5 to 95% non condensing
Timer/counters	Max: 40 timers; 32 counters (fixed)
I/O Scan time	0.21ms

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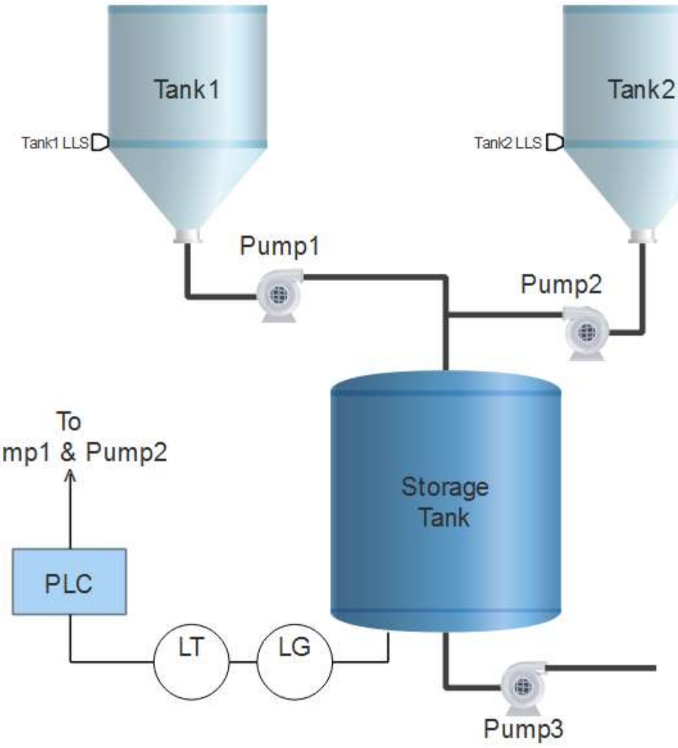

Figure 3.1: technical process plant with two tank and a mixer reactor (Amazon.com)

From the diagram in figure 3.1; the characterization is centered on the storage tank reactor where the necessary mixing and end production process occurs at a controlled temperature and concentration. The tank as shown in figure 3.2, mixed products from tank 1 and tank 2, while the plant is stirred continuously using the agitator plant. The specification of the plant is presented in the table 3.2 (amazon.com (plant specification)).

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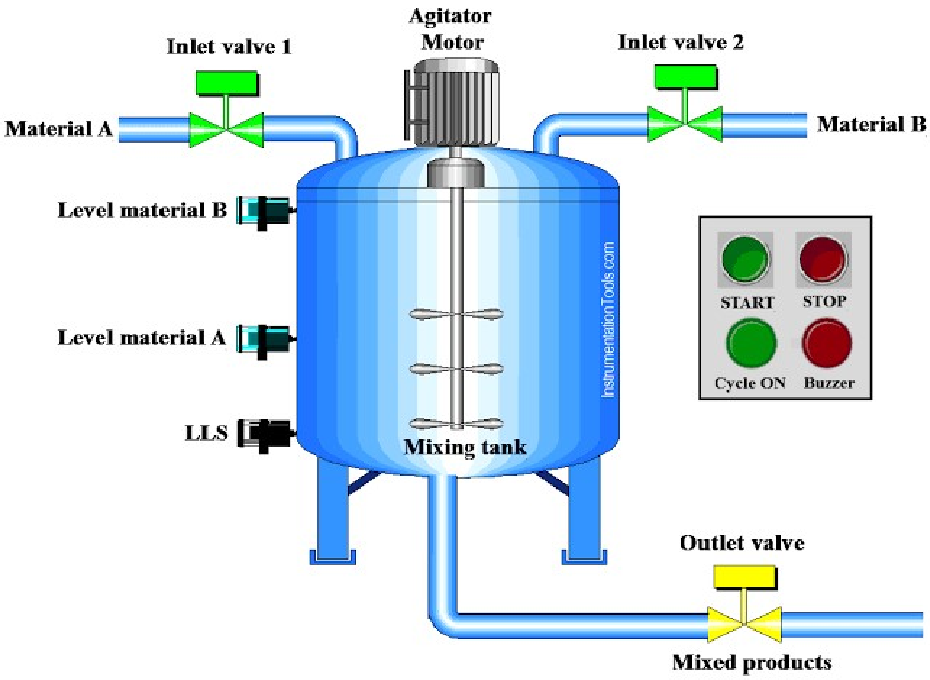

Figure 3.2: characterized continuous stirred tank reactor plant (Amazon.com)

Table 3.2: specification of the agitator plant

Industrial plant model	LGPT -02DN(F)/240V	
Toque	2NM	
Damper Area	0.5m²	
Running Time	35-45S	
Power Supply	AC/DC24V 50/60Hz	AC230V 50/60Hz
Operating Power Consumption	2W	1.5W
Plant type	Ac three phase Induction plant	
Control Signal	2/3 point	
Weight	0.6kg	
Angle of Rotation	0~90°(Max 93°)	
Rotate Direction	L/R switch	
Auxiliary Switch Rating	3(1.5) Amp 250V	
Life Cycle	>70000 cycles	
Noise Level	Max 45Db	
IP Protection	IP54	

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Temperature	-20~ +50°C
Humidity	S~95%RH
Storage Temperature	-40~ +70°C
Plant ID	Cocoa crushing machine

PLC controller is employed to monitor and control the temperature of the plant. The result of the PLC performance is recorded in the table 3.3 (plant manual collected from from Cadbury), considering the dominant time constant (**τ_1 and τ_2)** process gain k , and the closed loop time constant τ_c was selected to 0.5 min.

From the characterized result, the system will not attain complete steady state as the P_u (sec) varies with time, despite the PLC being tuned. Also it was revealed how the PLC performs at varying time, during operating condition of the plant as a linear time invariant (LTI) system, under varying temperature conditions as shown in figure 3.3, the result confirms the table 3.3 performance with the PLC, attaining a steady state at 3.5 seconds. This implies that the PLC did not achieve settling time, which is bad for a real time technical process control.

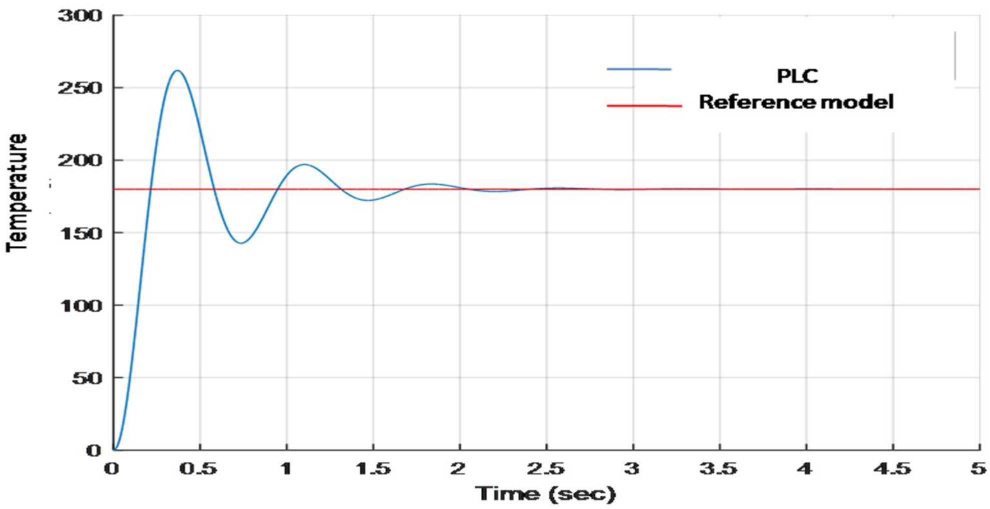

Figure 3.3: PLC performance on the CSTR

4. System Design

The system design was guided by the technical process architecture presented in figure 4.1. The input of the tanks was defined using as a transfer function using laplace transform. The relationship between the three inputs (tanks) and single output (CSTR) is defined as an auto regressive moving average (ARMAX) using iteration estimation method. In the CSTR since the temperature varies in the CSTR, the nonlinearity is presented by the signal variation related with the ARMAX using a polynomial model, this model presents the undesired signal which requires immediate control to prevent overheating and overflow.

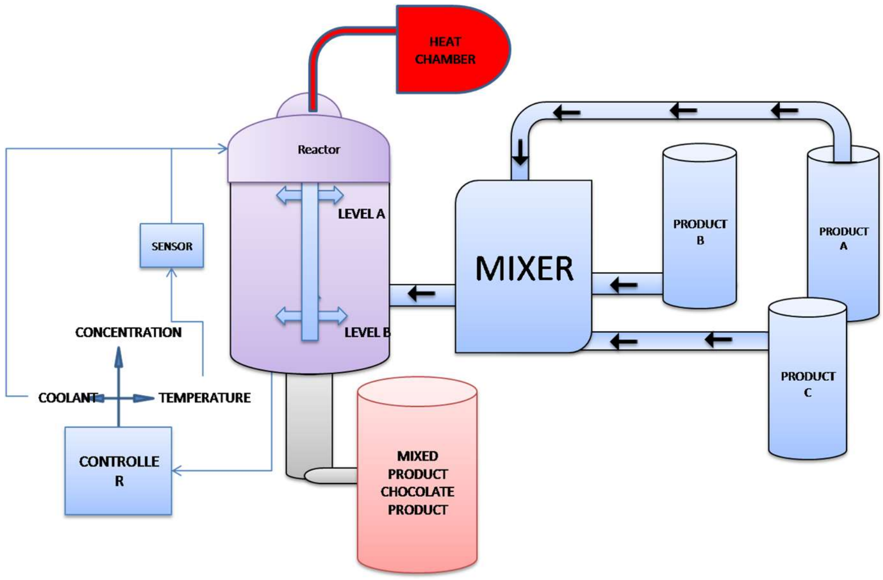

Figure 4.1: Proposed process plant to control

To develop the plant model, the input disturbance from the tanks, noise model (variation in concentration) and the output to the CSTR were considered first. These three models were related as a linear time invariant system (plant).

5. Results and Discussions

The aim of this chapter is to carryout simulation of the models developed and implemented in the chapter three. These models were developed using the necessary mathematical definitions in the form of transfer functions such as Laplace, Polynomials, estimation, dynamics and regressive models. Already the results of the two controllers have been presented in the previous chapter, however the training parameters for validation, testing and training data of the neural NNPC will be reported here. This chapter will also present the performance evaluation of the NNPC controller, and the result of the linearized hybrid controller on the proposed CSTR. The results will be discussed and evaluated using a comparative analysis to compare the three controllers considered in the cause of this thesis, which are the characterized controllers (PLC), the MPC and NNPC.

From the training process of the neural network, the training which is the dynamic input signal from the CSTR is presented alongside the plant output. Then the trained output performance of the neural network is presented which is the reference signal. The error between the reference signal and the plant output is presented as shown all in the figure 5.1.

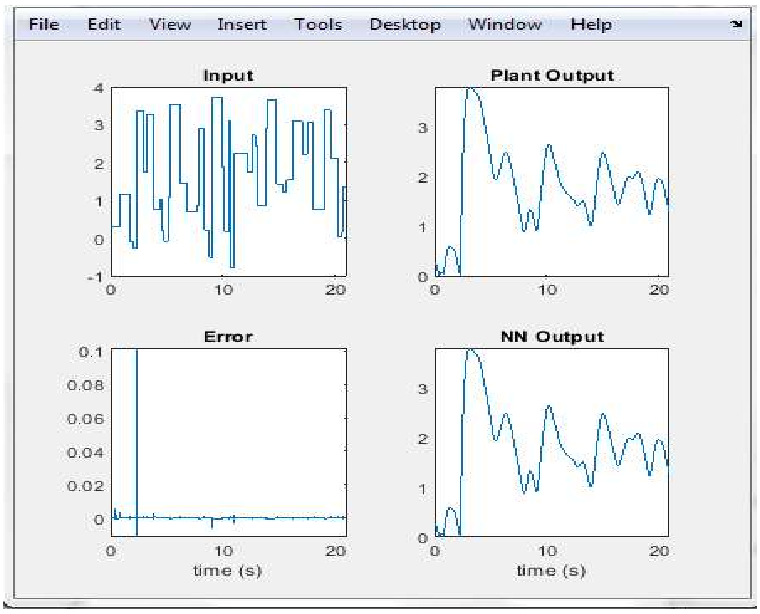

Figure 5.1: training result for the neural network controller

Form the result, it was observed that the plant output and the neural network output have a negligible error less than 0.01, the implication of this controller result shows a high level of system steady state, response time, and control result.

The controller was tested on a CSTR plant as shown in the simulink model of figure 4.1; the result is presented in figure 5.2; showing the plant input, error, controlled response and control signal. From the response of the NNPC, it was observed that the neural network output and the plant output have similar signal characteristics (zero error). The implication of this training is to know the real time performance of the controller on the proposed plant.

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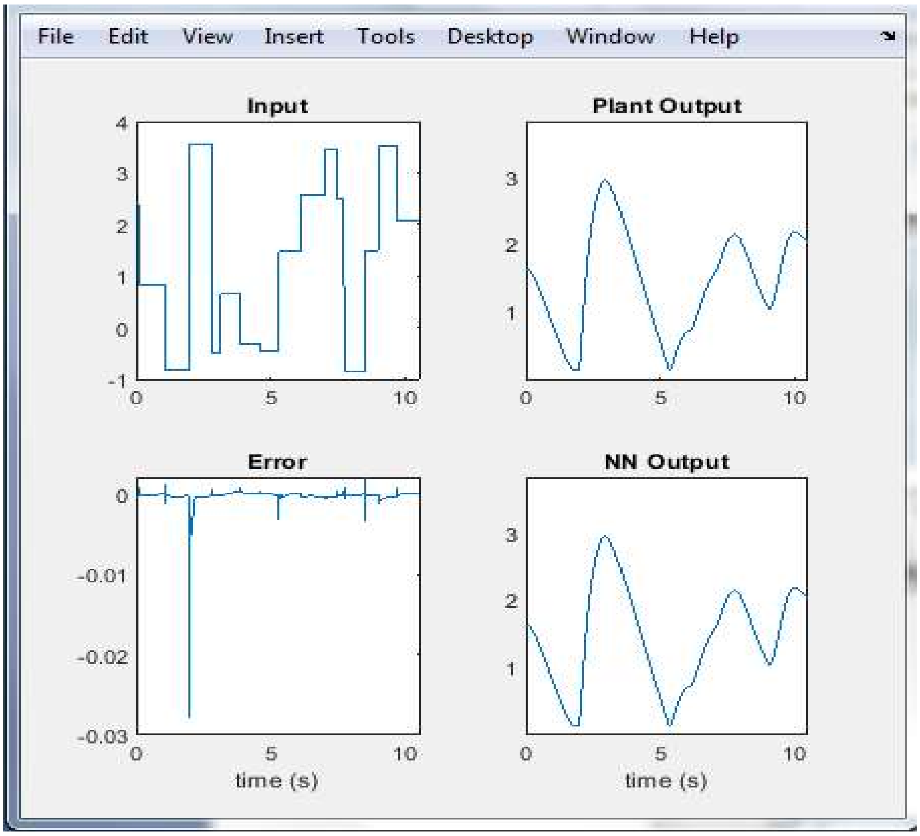

Figure 5.2: Figure: testing performance of the NNPC

Form the result, it was observed that the error signal between the training and the testing performance varies significantly. This is because the testing performance of the NNPC controller shows zero error between the plant output and the reference mode.

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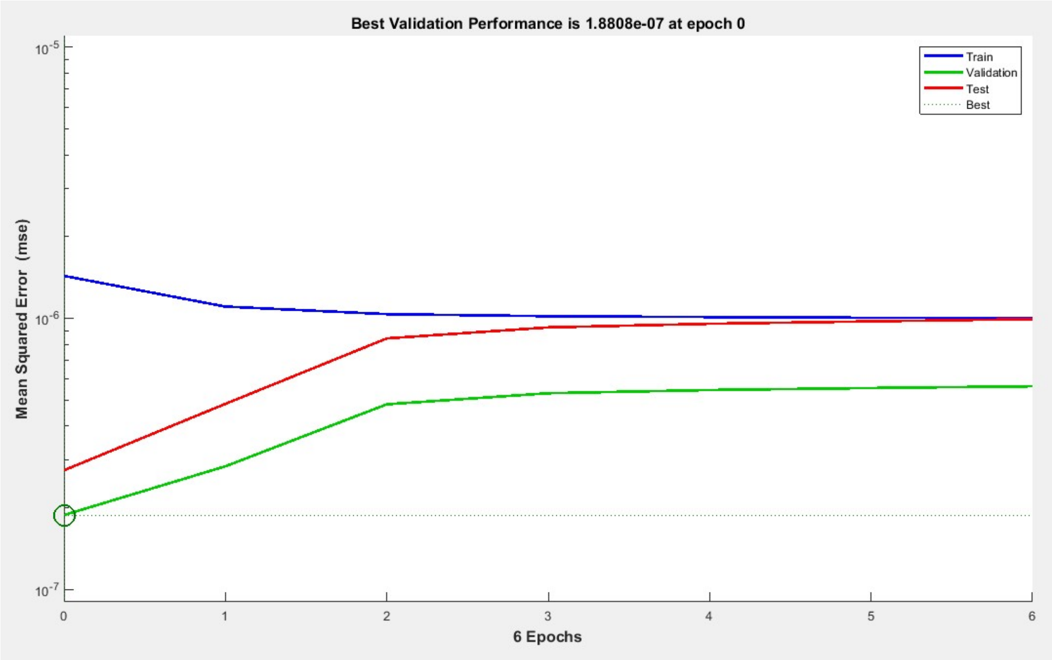

Figure 5.3: mean square error result

From the result, the output characteristics of the testing and training result of the controller are presented. it was observed that the training algorithm is perfect since the training and testing dataset produce likely result.

The result of the developed hybrid CSTR controller is presented in figure 5.4; the result shows that operating action of the hybrid controller on the reactor system. The result shows how the cotnroller closely follows the reference signal. From the result it was observed that when the temperature of the system rises above 300K, the system experience an unsteady dynamic response, the controller activates a coolant which stabilizes the system to steady condition.

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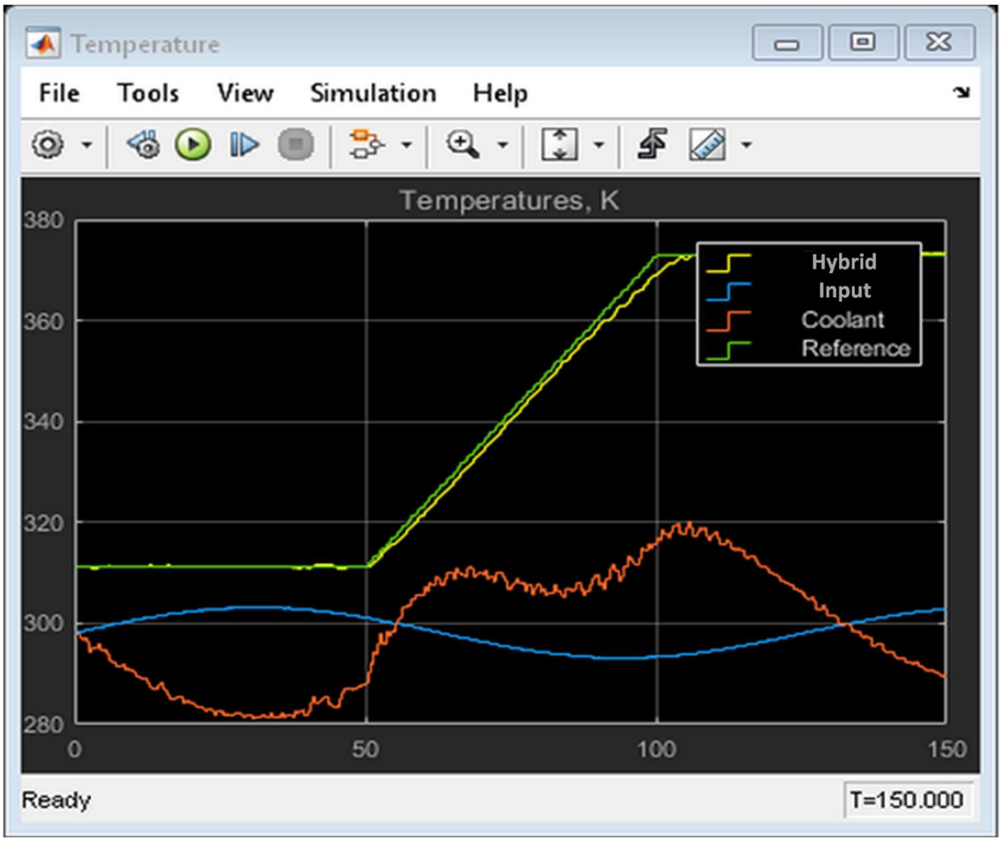

Figure 5.4: result of the hybrid on the plant

The performance of the hybrid controller is singled out and analyzed as a single structure to complete evaluate the response on the CSTR, as shown in figure 5.6, from the result, it shows that a complete optimization of the plant control performance has been achieved in terms of response time, steady state, zero overshoot and compelet system control. This shows that the combination of the model predictive controller and the neural network predictive cotnroller is perfect for the actualization of the proposed cotnrolled response.

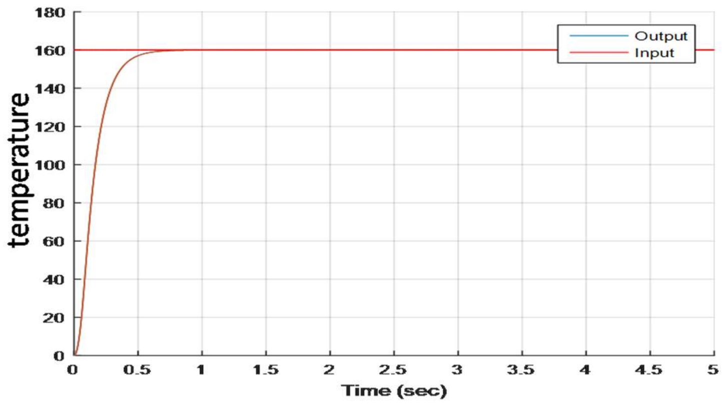

Figure 5.6: result of the hybrid temperature controller

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From the result, it was observed that the response time of the hybrid controller is 0.5secs, the steady state occurred at 0.5secs and zero overshoot. The implication of this result is that the hybrid controller responded to fault almost to the fault (over heating), immediately it occurred and rectified it.

To further justify the result and the performance of the hybrid controller, a comparative analysis will be performed, comparing all model predictive controller (MPC), tuned model predictive controller (TMPC) , the neural network predictive controller (NNPC) and the hybrid controller.

From the results of the NNPC, it was impressive, however the MPC performance more on settling time, because the MPC has no overshoot compare with the NNPC with overshoot. Also the MPC steady state was maintained at all times once the controller is active, however in the case of the NNPC, the stability of the system slightly varies every 5 sec of the controller operation. This shows that no controller is all perfect, that is they need a hybrid process to achieve precision. This was justified when the two controller were combined to control the CSTR, the result achieved was the desired result (showing the spontaneous reaction of the controller to fault and control action). This is shown in the result of figure 5.7;

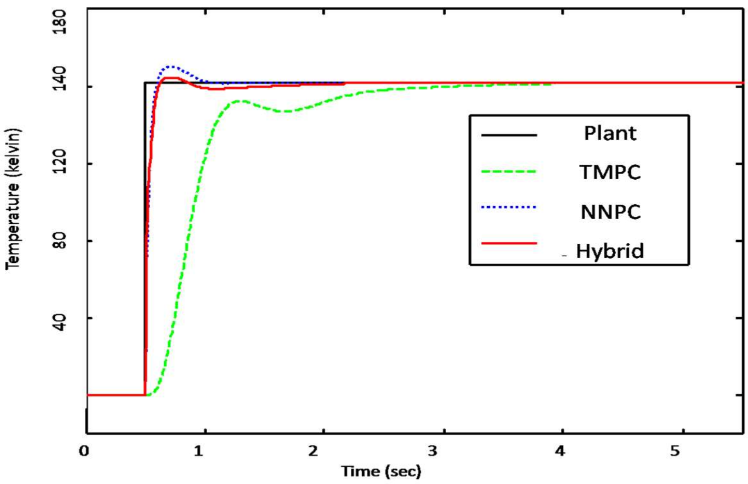

Figure 5.7: comparative result of the developed three controllers

From the figure 5.7, it revealed that the hybrid controller performs better than the other controller considered for the chemical reactor tank. This result is characterized and reported in table 4.2.

Table 4.2: comparative analysis of the developed controllers

Controller	**Response time sec**	**Steady state sec**	**Overshoot**	**Settling time (sec)**
PLC	0.3	2.5	Very high	2.5
MPC	4.0	20.0	Low	19.5
Tuned MPC	4.3	9.0	No overshoot	9.0
NNPC	0.3	2.0	Very Low	0.3
Hybrid	0.5	0.5	No overshoot	0.5

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