Real Time Implementation of MPC in Bottle Washer Machine for Small Scale Beverage Industry

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Abstract— **Temperature is the most critical parameter to ensure the proper cleaning of beverage containers in bottle washer machine. The requirement and importance of temperature control of different treatment zones of bottle washer machine for small scale beverage industry has been discussed. The sample water heating tank has been considered as the treatment zone of the bottle washer machine. The temperature control of the sample water heating tank with VIPA 315-SB PLC using PID control has been discussed and implemented. Two tuning methods for PID control, namely Ziegler Nichols tuning and auto-tuning have been discussed and implemented. The novel approach for implementation of MPC using OPC server and MATLAB as an OPC client has been discussed and implemented for sample water heating tank system. The comparison between PID and MPC temperature control schemes have been shown in terms of various performance indices. The results show that MPC provides better control and better performance compared to PID control scheme.**

Keywords—Bottle Washer Machine; MPC (Model Predictive Control); OPC (Object Linking and Embedding for Process Control); PID (Proportional Integral Derivative) Control; RGB (Returnable Glass Bottle); System Identification

I. INTRODUCTION

Beverage filling and packaging process involves various sequential stages such as picking up the bottles from crates, washing the used bottles, filling the beverage in bottles, labelling the bottles (in case of PET bottles) and putting the bottles in crates (in case of RGBs) or putting the bottles in cases (in case of PET bottles) [13].

The Bottle Washer Machine is an integral part of beverage filling and packaging process for RGB containers. In case of RGBs, the Bottle Washer Machine is used to clean the used bottles and in the case of PET bottles, the Bottle Washer Machine is used to rinse the bottles [13].

The conventional Bottle Washer Machine used in the large scale beverage industry has the bottle capacity of 10,000 – 1,50,000 bottles per hour [13]. However, the requirement of the small scale beverage industry is approx. 1000 – 2500 bottles per hour [1]. Therefore, considering the economical, functional and complexity aspects needed in the small scale beverage industry, it is necessary to scale down the existing Bottle Washer Machine. The design and development of the Bottle Washer Machine for small scale beverage industry has been discussed in [1]. The mechanical and electrical aspects of the design of the Bottle Washer Machine for small scale beverage industry along with the control logic sequence and simulation of PID temperature control of different treatment zones have been discussed in [1].

Temperature control of different treatment zones plays vital role in bottle cleaning process since the proper temperature of washing compound ensures thorough and residue-free cleaning of bottles. This paper focuses on the implementation of PID temperature control and more sophisticated control scheme, namely MPC temperature control for Bottle Washer Machine designed for small scale beverage industry.

The classical three term PID controller is used in more than 80% of industrial processes in a closed loop feedback manner and it provides an effective control for most of such processes [10]. The PID controller is tuned using Auto-tuning method, Ziegler Nichols method or transfer function obtained using reaction curve for satisfactory performance [3]. However, PID controller does not provide an effective action for the process having dead time [7]. In more complex systems, which exhibits non-minimum phase behavior or when the system is subject to constraints or under constant perturbations, the PID control is difficult to maintain and does not provide an efficacious control action [2].

One of the advanced control technique which can overcome the shortcomings of the PID control scheme and which has also become popular in the process industries, is Model Predictive Control (MPC) scheme. MPC refers to a family of advanced control methods, which explicitly use the process model to predict the future process behavior and to calculate a future control sequence by minimizing an objective function [10]**.** MPC scheme is mostly used for Multi Input Multi Output (MIMO) system, satisfying inequality constraints on input and output variables. However, MPC scheme can be also used for Single Input Single Output (SISO) system equally effectively.

Even though MPC scheme provides more sophisticated and superior control compared to PID scheme, MPC scheme still has not been generalized in terms of use in industrial processes [3], since most of the Programmable Logic

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Controllers (PLCs) do not have an inbuilt MPC function block unlike PID control scheme. Besides, PID control has been dominant in industrial process control due to its ubiquitousness and ease of implementation compared to other control strategies. Though some high end PLCs provide an inbuilt MPC function block, replacement of all the existing PLCs is an extravagant solution.

This paper proposes real time implementation of MPC in existing PLC controlled process without affecting the process itself, which in turn will provide better control compared to a conventional PID scheme. This paper discusses implementation of MPC on PLC for temperature control of Bottle Washer Machine using MATLAB Simulink and Object Linking and Embedding for Process Control (OPC) server. OPC server and client pair are used for communication between two different platforms over common communication protocol. The Water tank heating system has been considered as a sample treatment zone of the bottle washer machine and PID based temperature control as well as MPC based temperature control has been implemented on it. The comparison of MPC scheme with the PID control scheme for the water heating tank system has been shown and it has also been shown how MPC provides better performance compared to PID control, based on the comparison between various performance indices of the system.

II. SYSTEM HARDWARE AND SOFTWARE STRUCTURE

The design and working of the bottle washer machine used in small scale beverage industry has been discussed in [1]. Out of three treatment zones of bottle washing machine, namely pre-heating zone, caustic zone and hydra zone, the temperature control is required for the adjacent caustic zone and the hydra zone [1]. The temperature control of the bottle washer machine poses the interacting tanks' temperature control problem, which is actually a MIMO system control problem. MPC is an ideal control scheme to solve such kind of MIMO process control problem [8]. Since the coupling between different treatment zones is not so strong, this paper considers MPC implementation of the single treatment zone by considering water tank heating system, which is a SISO system control problem. Since the implementation approaches of MPC for SISO system and MIMO system remains same, the MPC scheme can be easily extended for MIMO system with some modifications.

The experimental setup for single tank temperature control by using VIPA 315-SB PLC and CP343-1 Ethernet lean module is shown in Fig. 1 and has been explained in [1].

The water in the tank is heated by 230 V AC supply operated immersive type of heating rod. The Unison zero crossing type relay is used as a switching element, to turn on and turn off the heater. It operates on 24 V DC provided by the PLC and turns on and turns off the heater by providing and withholding 230 V AC on the output side. The IFM TA-3430 Pt1000 RTD has been used as a temperature sensor.

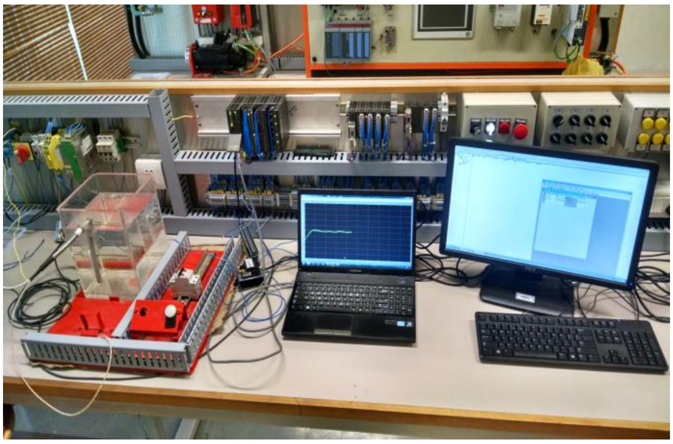

Fig. 1. Water Heating Tank System with VIPA 315-SB PLC

The controller, sensors and instruments used in water heating tank system is listed in Table I.

TABLE I. CONTROLLER, INSTRUMENTS AND SENSORS USED IN WATER HEATING TANK SYSTEM [1]

Instrument/Sensor	Input supply	Output
VIPA 315-SB PLC	24 V DC	4 – 20 mA / 24 V DC
Pt1000 RTD (IFM TA3430)	24 V DC	4 – 20 mA
SSR (Unison 801 ZDA 48 50 01)	4 – 32 V DC	24 – 480 AC
Heater	230 V AC	Heating Energy

The programming of VIPA 315-SB PLC has been accomplished using SIMATIC Manager. The PID temperature control of water heating tank system has been accomplished using FB58 (Function Block 58) in SIMATIC Manager. For MPC implementation, MATLAB has been used for control algorithm implementation and KEPServerEX has been used as an OPC server. It is not possible to establish direct communication between MATLAB and VIPA 315-SB PLC due to communication incompatibility between them. Therefore, KEPServerEX works as an OPC server, which provides common communication protocol between MATLAB and VIPA 315-SB PLC.

III. PID TEMPERATURE CONTROL OF WATER HEATING TANK SYSTEM

The closed loop temperature control of water heating tank system using PID control scheme has been shown in Fig. 2.

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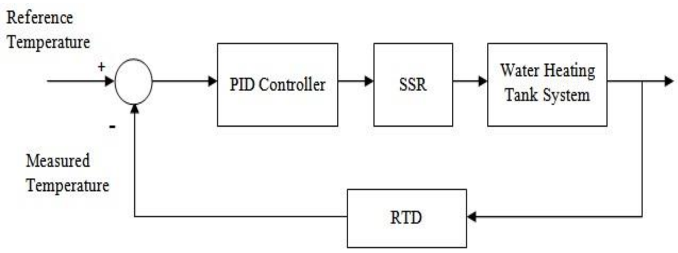

Fig. 2. Closed loop PID temperature control of water heating tank system

The desired temperature is given as a reference temperature to PID controller. The temperature of water inside the tank is measured by Pt1000 RTD. The measured temperature by RTD is compared with the reference temperature and based on the error generated, PID controller gives the output to Solid State Relay, which acts as an actuator for water heating tank system.

The closed loop PID temperature control scheme has been implemented for the experimental setup shown in Fig. 1. SIMATIC Manager provides closed loop PID temperature control interface with VIPA 315-SB PLC in terms of FB58 function block. The FB58 block based on the error generated due to the difference between the desired temperature and measured temperature, provides the PID controller output in terms of PWM. Based on the duty cycle of PWM, SSR does the switching and following the switching of SSR, heater gets turned on and off accordingly. The complete configuration procedure for closed loop PID temperature control has been discussed in [1].

The satisfactory performance of the PID controller is ensured by proper tuning of proportional gain K_p, integral gain K_i and derivative gain K_d. There are numerous techniques available to tune the PID controller, out of those, Ziegler Nichols method and auto-tuning method is discussed over here.

A. Ziegler Nichols Tuning of PID Temperature Control

Ziegler Nichols tuning is widely accepted method in process industries, for manual tuning of PID [5]. The Ziegler Nichols tuning method uses the concept of quarter amplitude damping [6]. Based on the Ziegler Nichols heuristic approach, the proportional, integral and derivative gains can be calculated [9].

Using the Ziegler Nichols tuning method, the values obtained for ultimate gain K_u and ultimate period P_u are 60 and 160 seconds respectively for the water heating tank system. Based on the values of K_u and P_u, the values of proportional gain K_p, integral time T_i and derivative time T_d are 39 seconds, 80 seconds and 20 seconds respectively.

The step response of PID temperature controller tuned using the Ziegler Nichols tuning method for 1 °C step change is shown in Fig. 3.

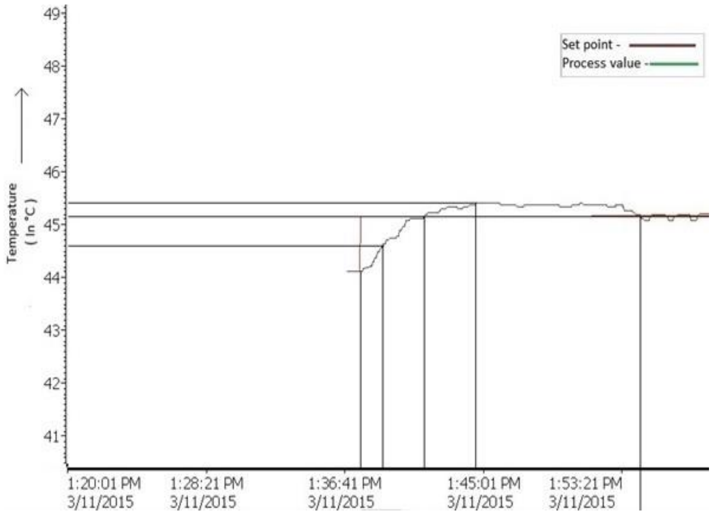

Fig. 3. Step response of PID temperature controller for Ziegler Nichols Tuning

B. Auto Tuning of PID Temperature Control

Auto-tuning method is used to tune the PID controller automatically based on the demand of user. The auto-tuning method eliminates the need to understand the process dynamics as well as eliminates the need to perform experiments to determine the gains of PID controller. Industrial survey has shown that auto-tuning is highly desirable and important feature for the tuning of PID controllers [11].

For auto-tuning method, the values obtained for K_p, T_i and T_d are 53.46 seconds, 135.67 seconds and 35.68 seconds respectively for the water heating tank system.

The step response of auto tuned PID temperature controller for 1 °C step change is shown in Fig. 4.

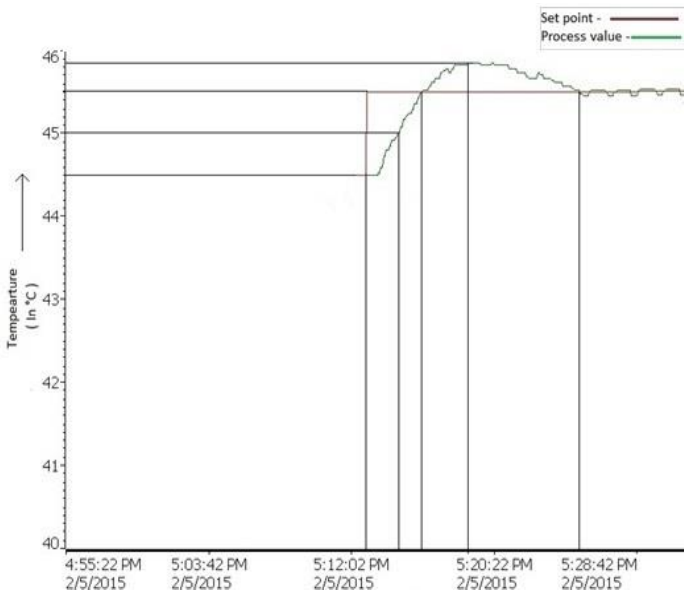

Fig. 4. Step response of PID temperature controller for auto-tuning

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IV. IMPLEMENTATION OF MPC ON PLC

MPC refers to a family of the controllers, which explicitly use process model to obtain the controller output by minimizing an objective function [4,7]. The MPC mainly consists of three different elements: (1) Prediction Model, (2) Objective Function and (3) Control law. The model is the most important part of MPC strategy, since the future outputs and control law predicted by the algorithm is determined by using the model. Two types of model, namely process model and disturbance model (if available), are used in MPC scheme. The required process model of water tank heating system has to be obtained for successful implementation of MPC scheme, which can be obtained by using a system identification toolbox of MATLAB. For system identification of water heating tank system, it is necessary to obtain the relation between input and output parameters by establishing a successful communication channel between MATLAB and PLC. This communication channel between MATLAB and PLC can be established by configuring the OPC server and MATLAB as an OPC client.

A. Configuration of MATLAB as an OPC Client and PLC as an OPC Server

OPC technology is a hardware and software interface standard using Client/Server mode based on COM (Component Object Model)/DCOM (Distributed Component Object Model), which offers a general standard mechanism for the client's and server's data communication and exchange and supports the network distributional application procedure communication as well as the application procedure communication in different platforms [4]. By using the MATLAB OPC Toolbox, we can realize advanced control of complicated industrial processes based on the network environment to improve control efficiency.

The OPC server KEPServerEX has been configured to communicate with the VIPA 315-SB PLC with CP 343-1 ethernet lean module using Ethernet communication protocol as shown in Fig. 6.

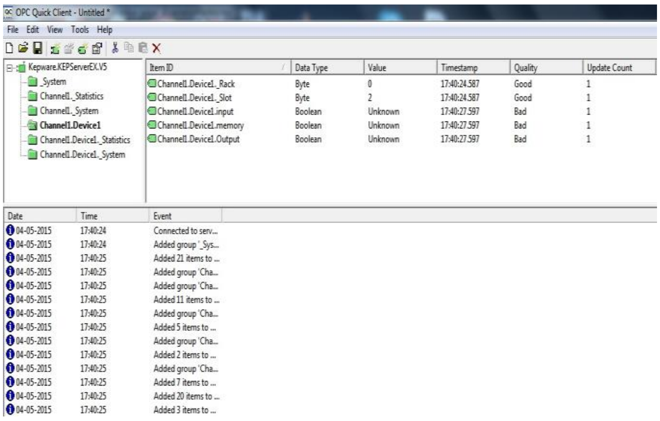

Fig. 5. Configuring KEPServerEX as an OPC Server

MATLAB has been configured as an OPC Client to communicate with PLC through KEPServerEX using Ethernet cable. The configuration of MATLAB as an OPC Client has been shown in Fig. 6.

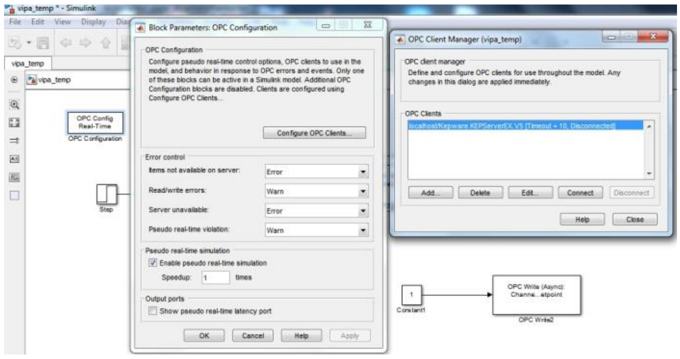

Fig. 6. Configuring MATLAB as an OPC Client

B. Acquisition of Process Model using System Identification Toolbox in MATLAB

System or process identification is the field of mathematical modelling of systems (processes) from test or experimental data [12]. The input-output data are usually collected from an identification test or experiment that is designed to make the measured data maximally informative about the system properties that are of interest to the user [12].

The system identification toolbox of MATLAB provides a mathematical model of the system based on the input-output data. This approach is quite popular in industries since it does not require the mathematical formulation of process dynamics from the user. On the contrary, it provides the mathematical model based on empirical data only and the user does not require to have the complete understanding of process dynamics.

For the water heating tank system, 1°C step change is given to the process and the corresponding relation between voltage applied to a heater and temperature of the tank have been captured using MATLAB Simulink model as shown in Fig. 7.

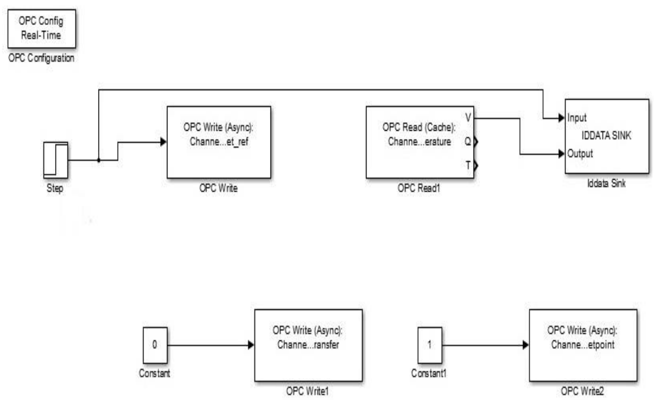

Fig. 7. MATLAB Simulink Model for system identification of water heating tank system

The captured input-output relation between heater voltage and temperature of the tank has been stored as a data object in MATLAB workspace as shown in Fig. 7. This data object has

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been used to determine the transfer function of the water heating tank system using system identification toolbox as shown in Fig. 8.

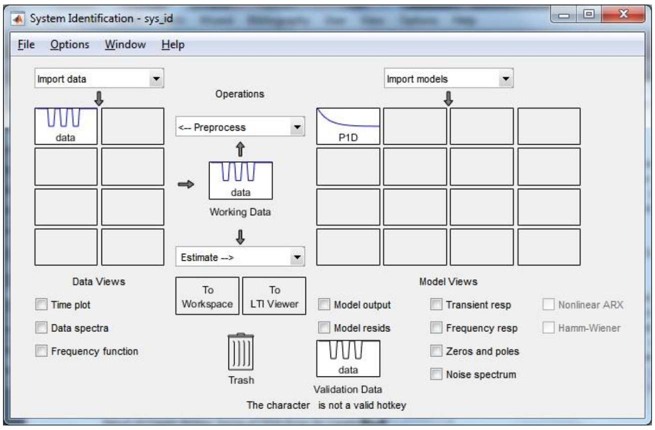

Fig. 8. System identification toolbox for determination of transfer function of water heating tank system

The estimated transfer function of water heating tank system obtained by system identification toolbox is given as,

$$G(s) = \frac{3.25}{1+672.6s} * e^{-2s} \quad (1)$$

The obtained transfer function in (1) has been used as a mathematical model for the implementation of the MPC temperature control scheme.

C. Real time implementation of MPC in PLC using MATLAB as OPC Client

The MPC control scheme has been implemented after the successful communication between MATLAB and PLC through OPC server and acquisition of process model using system identification.

The MPC parameters are configured in control and estimation tools manager of MATLAB as shown in Fig. 9.

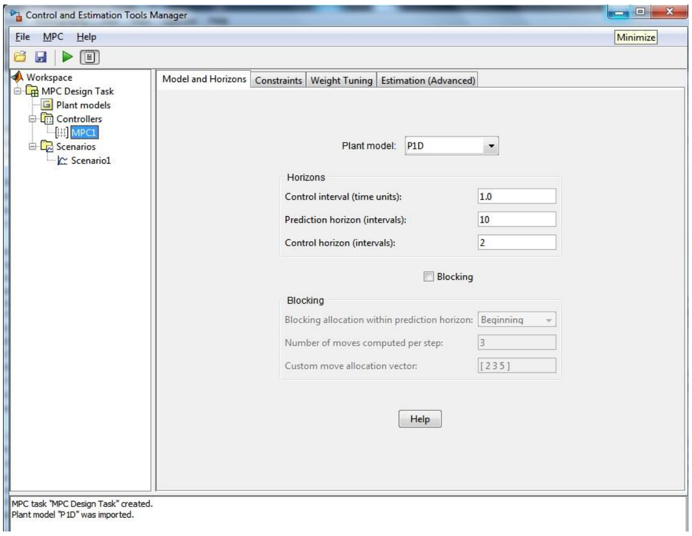

Fig. 9. MPC Parameter configuration in MPC Design Tool

The process model obtained in (1), has been called in control and estimation tools manager of MATLAB and prediction horizon and control horizon of MPC scheme have been kept at 10 seconds and 2 seconds respectively, as shown in Fig. 9. The values of prediction horizon and control horizon can be changed, based on the requirement of aggressiveness of control or robustness of control.

The constraints on the controller output (or manipulated variable u) has been kept from 0 to 100. The MPC scheme for temperature control has been configured using MATLAB Simulink model as shown in Fig. 10.

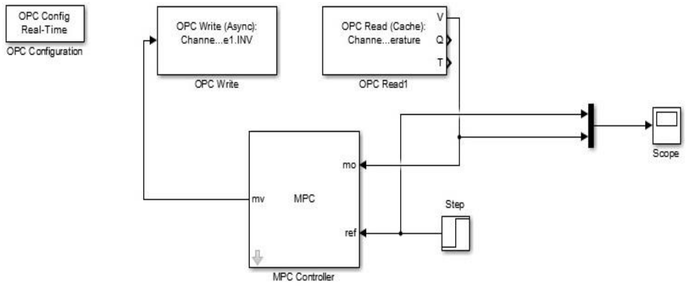

Fig. 10. MATLAB Simulink Model for MPC based Temperature Control Scheme of Water Heating Tank System

The OPC Configuration block connects the MATLAB as an OPC Client with OPC Server KEPServerEX as shown in Fig. 10.

The controller output from MPC, has been given to FB43 “PULSEGEN” block of the PLC through the OPC Write block, which converts the value of controller output into a corresponding PWM signal. This PWM signal has been given to SSR, which turns on and off the heater, based on the value of the PWM signal. The measured temperature of water heating tank system has been measured through Pt1000 RTD and has been given to the MPC controller to compare with the reference temperature value. Therefore, the closed loop temperature control using MPC scheme has been implemented as shown in Fig. 2.

The step response of the MPC temperature controller for 1°C step change for water heating tank system is shown in Fig. 11.

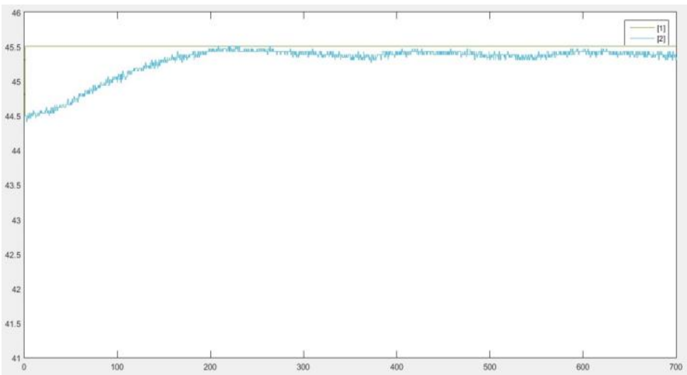

Fig. 11. Step response of MPC temperature controller

The slight dip (or undershoot) in step response in Fig.11 is due to the tolerance limits provided to SSR. The tolerance limits for SSR is given so that high frequency switching for small errors is avoided, which can cause the damage or failure of the heater.

V. RESULTS

The temperature control of water heating tank system has been implemented using PID control and MPC schemes. The PID controller has been tuned using two methods,namely Ziegler Nichols tuning and auto-tuning. The comparison of performance of PID controller and MPC controller, in terms of various performance indices has been shown in Table III.

In terms of peak overshoot (Mp), delay time (Td), peak time (Tp) and settling time (Ts), performance of MPC controller outweigh the performance of PID controller. However, the transient response of auto-tuned PID controller is better compared to MPC, but it does not hold much significance since the response of MPC settles at the value of rise time. It is clearly evident that MPC performs superiorly compared to Ziegler Nichols tuned PID controller and MPC for all the performance indices except for rise time.

TABLE II. COMPARISON OF PID CONTROL SCHEME AND MPC SCHEME FOR TEMPERATURE CONTROL OF WATER HEATING TANK SYSTEM

Performance Indices	Ziegler Nichols tuned PID Controller	Auto-tuned PID Controller	MPC Controller
Peak Overshoot (M_p)	26%	28%	0%
Delay Time (T_d)	110 seconds	120 seconds	90 seconds
Rise Time (T_r)	260 seconds	150 seconds	208 seconds
Peak Time (T_p)	460 seconds	300 seconds	208 seconds
Settling Time (T_s)	1080 seconds	208 seconds	208 seconds

VI. CONCLUSION

The temperature control of the bottle washer machine for small scale beverage industry has been achieved by using PID control scheme as well as by using MPC scheme. The PID controller has been tuned using two different tuning methods, namely Ziegler Nichols tuning and auto-tuning method.

The PID control scheme does not perform satisfactorily for the system having dead time, the system having constraints and multivariable control problem. The limitations imposed by the PID control scheme can be overcome by an advanced control scheme such as MPC. However, the existing PLCs in industrial processes do not support the advanced control schemes and the replacement of the existing PLCs for implementation of advanced control scheme is an extravagant solution. Therefore, the novel approach for implementation of the MPC scheme on existing PLCs using OPC server and MATLAB as an OPC Client has been proposed and implemented. The comparison of PID temperature control and MPC temperature control has been made. The results show that the performance of MPC scheme is better compared to PID control scheme in terms of various performance indices. The results obtained for sample water heating tank can be easily extended for different treatment zones of the bottle washer machine. The future work can be extended by generation of C/C++ code using MATLAB PLC Coder for advanced control scheme implementation in existing PLCs.

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