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Comparative Study of Different Supervisory Control Structures

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***Abstract*— With the advent of computer control, supervisory controllers such as simple cascade control, model predictive control (MPC), dynamic matrix control (DMC), etc are increasingly being used in process industries. In this study, performance of three such controllers namely simple cascade controller, 'MPC cascaded to PID' and 'PID free MPC' are compared on a continuous stirred tank heater (CSTH) system. In the MPC cascaded structure the flow-loops are regulated by the PID controller. On top of that a DMC manipulates the set-points of the flow-loops to control tank temperature and level. The 'PID-free MPC' structure uses a DMC to manipulate the valve positions directly. The study reveals that the PID-free MPC structure outperforms the cascade structure in both disturbance rejection and set-point tracking. However, the PID-free MPC structure demands more control action and has more control load. Integrated square error (ISE) is used to quantify the performance.**

I. Introduction

Model predictive controllers are typically used as a supervisory layer above the base level PID controller, especially in large-scale applications. This structure gained acceptance mainly because it allows the implementation of MPC with minimal changes to the existing control structure. Also, the PID layer can act as a fall back when the MPC is turned off for any reason. However, this structure does not allow the potential benefits of the MPC to be fully harnessed. In practice, it was observed that there are many incentives in breaking the PID loop and directly manipulating the valve output using the MPC. One common example is when trying to use the full valve capacity (e.g., maximize feed, maximizing cooling) it is common practice to break the PID loop and manipulate the valve directly from MPC.

Recently, a software called MaxAPC from the original inventors of DMC is being marketed that uses the DMC to directly manipulate the actuator [1]. It is claimed that this controller performs better than the MPC cascaded to PID structure. Therefore, an objective investigation of the performance of these competing control structures is necessary. In this study, a simulation-based comparative study is carried out between two control structures: MPC cascaded to PID and MPC directly manipulating the valve output.

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II. Literature Review

A. Current State of PID Controller

PID is a widely used control structure in the industry. Desborough and Miller estimated that 98 percent of the controllers in a median chemical plant are PID controllers [2]. Though it is widely used for its simplicity of implementation, it has different limitations. The main limitation of the PID is that it has no straightforward tuning method. The impact of this fact is evident from the result reported by Van Overschee and De Moor [3]. They concluded that 80 percent of industrial PID controllers are poorly tuned; 30 percent of these PID loops operate in manual mode; and 25 percent of the PID loops in automatic mode operate under default factory settings.

A control structure to overcome the drawbacks of the conventional PID controller with fixed tuning parameters, was proposed in [4], where PID gains are automatically tuned in order to keep a predefined cost function to a minimum. The applied methodology showed superior performance compared to PID in both set point tracking and regulatory control. Another simple but robust technique is described in [5], combining the simplicity of PID and versatility of MPC together. In this work tuning parameters are defined based on the key performance indices such as set point tracking, disturbance rejection, and the robustness and aggressiveness of the controller. The controller showed better performance in set point tracking and disturbance rejection compared to an IMC-tuned PID controller in extensive simulation studies. The potential alternatives for PID in industrial settings are investigated in [6]. Discrete-time linear MISO controller, state feedback and observers (SFO), model predictive controller (MPC) and fuzzy control are mentioned as potential alternatives. All alternatives showed improved performance, especially for poorly damped systems. Controllers based on SFO require a greater modeling effort, as such its use is justified only when modeling efforts are moderate. MPC is typically used as a supervisory layer to the base layer PID. The use of MPC provides a drastic improvement of set point tracking. Moreover, computational complexity is minimized in this case, as MPC executes at a slower rate, regulating the slower dynamics of the system. The PID layer reacts for the fast interactions. Pannocchia et el. proposed an offset-free constrained linear quadratic (CLQ) controller as a potential candidate to replace PID [7]. CLQ consists of three main modules based on a state-space model of the system: a state and disturbance estimator, a constrained target calculation module, and a constrained dynamic optimizer. Each module is designed to minimize the computational load and, as such, the controller implementation load is comparable to a PID controller. The CLQ controller outperformed the PID controller in all the simulated cases reported in the paper. The controller was limited to SISO systems, however, it may be extended for MIMO systems. Hans described active disturbance rejection control (ADRC) as an improved control scheme to replace PID [8]. ADRC is error driven similar to PID, using a state observer to utilize the power of non-linear feedback. ADRC is aimed at overcoming these PID limitations using a non-linear control law instead of a simple weighted error.

Though various controllers have been proposed as an alternative to PID controllers, MPC has probably the most potential to replace a portion of the PID controllers in process industry. In the following subsection, some of the articles that compared MPC with PID, are reviewed.

B. *Comparative Study between MPC and PID*

A comparative study between standard PID and predictive controller is presented for a heat exchanger in [9] where an identified model is used to design PID controller and Generalized Predictive Control (GPC). GPC provides better performance compared to standard PID for both set-point tracking and disturbance rejection. In another work [10], MPC is implemented for a heat exchanger presented in to optimize and conserve energy. Model predictive controller and PID controller for this system were designed and used to control the temperature of a fluid stream. Comparative studies on the two controllers' performance show that MPC provides better performance based on the rise time, overshoot and settling time. A comparative study of PID controllers, MPC controllers and model free adaptive controllers (MFA) is performed in [11]. The results show that PID is the fastest of the three controllers but it has overshoot and steady state error. Both MFA and MPC are steady state error-free. MFA tracks the set point faster than MPC, but MFA has overshoot.

The above literature survey shows, even though there were several studies to evaluate the performance of MPC against PID controller, there was no effort to compare the performance of two important control structure: MPC cascaded to PID and PID directly manipulating actuator. This study is aimed to conduct such a comparative study.

III. Plant Description

We chose a simulated continuous stirred tank heater (CSTH) [12], as our system to conduct the comparative study. Though the plant is a simulated model, it is very realistic as it uses actual measurement noise and disturbances along with the dynamic equations. The available simulink model is considered as a plant for this study.

In this set up, water is heated using steam and hot water. Cold water enters into the tank continuously from supply. Steam is supplied from a boiler whereas hot water is supplied from building utilities. Control valves manipulate the flow of steam, cold water and hot water. The water level of the tank and the temperature of the water are the two controlled variables. These variables are controlled by manipulating the valve positions of the control valves. Standard operating points used to develop simulink model are stated in Table I.

TABLE I
Operating points of CSTH for different control structures

Variable	Op Pt
Level/cm	20.50
Temperature/Deg C	42.50
CW valve/percent	42.67
Steam valve/percent	40.81
HW valve/percent	0

TABLE II
Identified transfer function models

Variables	**CW valve**	**Steam valve**
Level/cm	$\frac{5.75e^{-s}}{261s+1}$	
Temperature/Deg C	$\frac{-0.415^{-9s}}{36s+1}$	$\frac{0.81e^{-8s}}{41s+1}$
CW flow	$\frac{0.3}{20s+1}$	
Steam flow		$\frac{0.225}{s+1}$

For control purpose first order models of the process variables for the change in cold water valve and steam valve, are identified. These open loop models are used to tune PID as well as to design DMC controllers. Identified open loop models are provided in Table II.

IV. Control Structures

In this work, the performance of three different control structures are compared. These are: a two-layer cascaded PID structure; a hybrid structure with PID in the base layer and the set-points of the PID manipulated by DMC; a PID-free structure where the control valve is directly manipulated by DMC.

A. *Two Layer Cascaded PID Structure*

The cascaded PID structure is presented in Figure 1 using the four measured variables and two manipulated variables. Cold water flow and steam flow are the two measured variables used as the feedback to the base layer PID. The outputs of the base layer PIDs are used to manipulate the position of the control valves of cold water and steam. Set-points of the base layer PID controllers are manipulated by supervisory layer PID. Measured variables, tank level and temperature, are used as feedback signals to the supervisory layer PID, which compares the measured values with their corresponding desired values and provides control actions accordingly.

B. *DMC Cascaded with Base Layer PID*

The hybrid control structure is shown in Figure 2. In this structure, the supervisory layer is a DMC controller. This

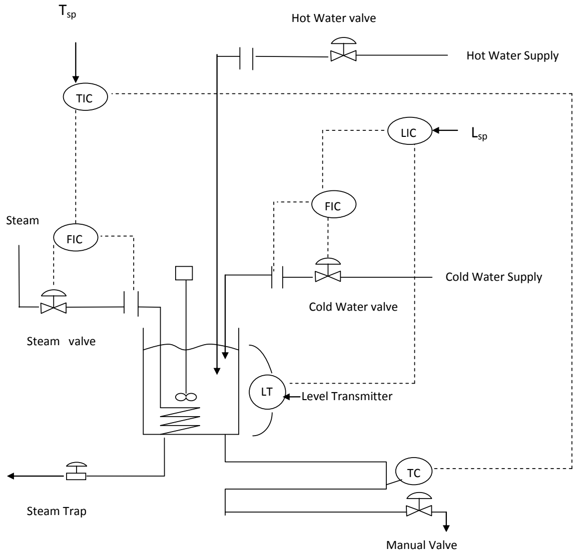


Fig. 1. Two layer cascaded PID structure

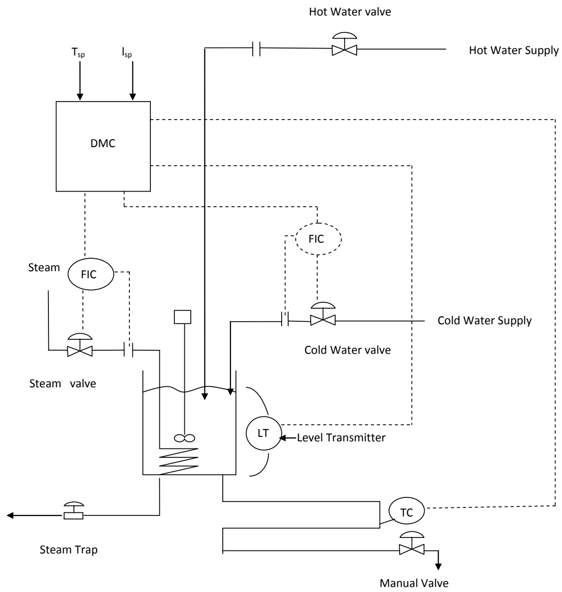


Fig. 2. DMC cascaded with PID structure

structure is practised widely and gained acceptance mainly because it allows the implementation of MPC with minimal changes to the existing control structure, and also because the PID layer can act as a fall back when MPC is turned off for any reason. In this structure, the plant, together with the PID controller, constitutes the system for the MPC that controls the tank level and temperature by manipulating the set-points of the base layer PID flow controllers. In order to design the MPC for this structure models of level and temperature were identified for the change of cold water flow PID set point and steam flow PID set point. Identified first order transfer functions for this structure are given in Table III.

TABLE III
IDENTIFIED TRANSFER FUNCTION MODELS FOR FLOW PID SET POINTS

Variables	CW Flow	Steam flow
Level/cm	$\frac{3.875e^{-s}}{289s+1}$	
Temperature/Deg C	$\frac{-0.32e^{-9s}}{48s+1}$	$\frac{0.7325e^{-8s}}{32s+1}$

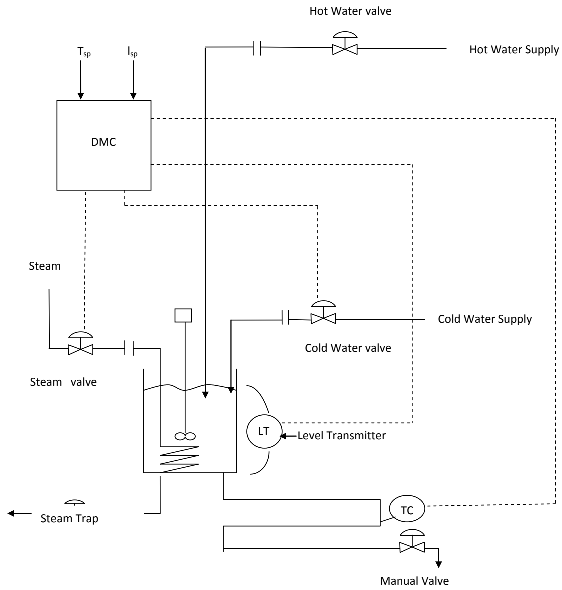


Fig. 3. PID free control structure

C. PID Free MPC Structure

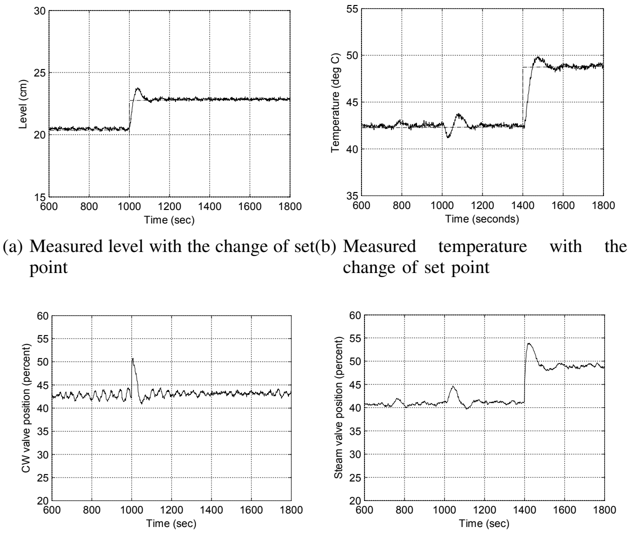
A PID-free control structure is presented in Figure 3. In this control structure there is no PID controller. A DMC controls the tank level and temperature by manipulating the cold water valve and the steam valve positions directly. DMC is designed using the open loop model stated in Table II.

V. PERFORMANCE COMPARISON OF DIFFERENT TYPES OF STRUCTURES

The performances of the three different control structures are evaluated based upon set point tracking and regulatory control. Set point tracking performance describes how well a controller can react to the change of the desired set point of a process variable, whereas regulatory control assesses the ability of the controller to nullify the effect of any disturbance that appears in the system. Apart from these two properties, another desired property of a good controller is minimal fluctuations in the actuator. This will also be evaluated in this study.

A. Set-point Tracking

For assessing the controllers' performance to a change in set point, the same scenario was set for the three different structures. The set points of both level and temperature are changed and the change of measured variables and actuator due to control action are observed. Measured outputs and



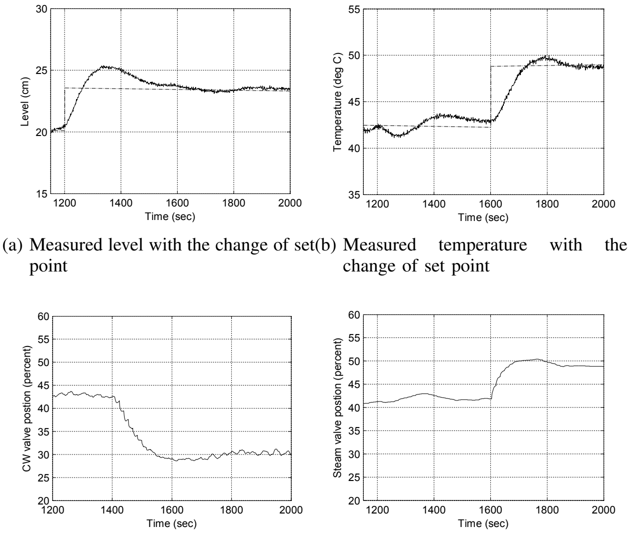
(a) Measured level with the change of set point

(b) Measured temperature with the change of set point

(c) Cold water valve position

(d) Steam valve position

Fig. 4. Measured output and actuator variable in cascaded PID structure for set point change



(a) Measured level with the change of set point

(b) Measured temperature with the change of set point

(c) Cold water valve position

(d) Steam valve position

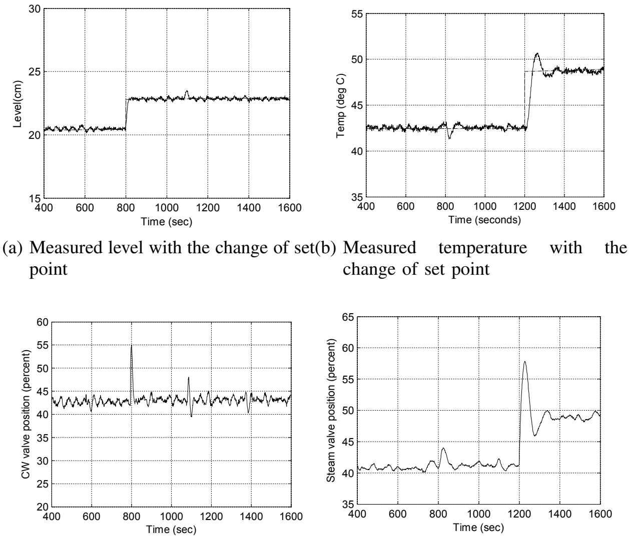
Fig. 5. Measured output and actuator variable in hybrid structure MPC for set point change

manipulated variables for the three controllers are shown in Figures 4 to 6. The set point of the level is changed from 20.5 to 22.85 cm and the temperature set point is changed from 42.5 to 48.73°C. From the figures, it is evident that a PID-free MPC structure can react to a change of set point quicker than the other two structures; however, it demands more movements in the actuators. Considering valve movement, a hybrid structure proved to be better. However, it is much slower to react to the set point change. Both cascaded PID and hybrid structures have some overshoot which is much lower in the case of PID-free MPC. Execution frequency is another concern while designing DMC. In hybrid structure, DMC execution frequency is 15s, while for PID free structure execution frequency is 1s in order to reject any local disturbances. Hence, a PID-free structure has significantly more computational load compared to the hybrid PID.

In order to quantify the control performance of the three structures, they are compared using the integrated squared error (ISE) values for set-point tracking. ISE value is an integrated value of the deviation between the desired set-point and measured output over a certain period. In this case, an integral interval is considered to be the time that is required to achieve a steady state value after a set-point is changed. The ISE values for level and temperature are shown in Figures 7 and 8. From the figures, it can also be seen that the PID free structure shows superior performance compared to other structures. The DMC-PID control structure gives a larger ISE value due to steady state error. To sum up, having a large computational load PID-free structure is bit difficult to implement but it clearly outperforms the other structures in terms of control performances.

B. Regulatory Control

Regulatory control assesses a controller's ability to nullify a disturbance when it enters into the system. In this study,



(a) Measured level with the change of set point

(b) Measured temperature with the change of set point

(c) Cold water valve position

(d) Steam valve position

Fig. 6. Measured output and actuator variable in PID-free MPC structure for set point change

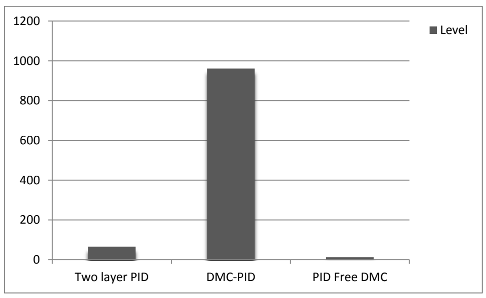


Fig. 7. Comparison of the ISE value of different control structures for level control

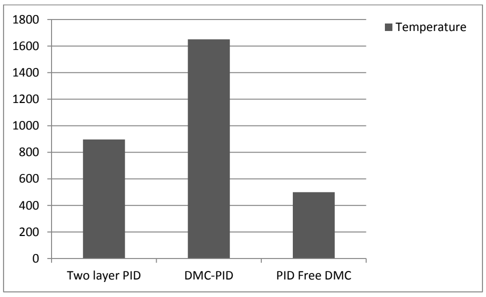
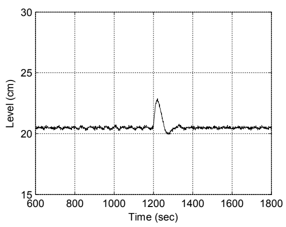
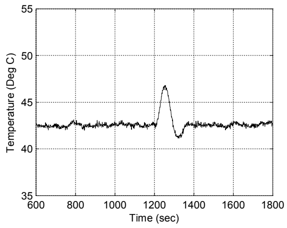


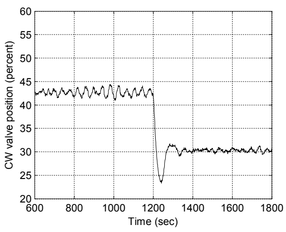
Fig. 8. Comparison of the ISE value of different control structures for temperature control



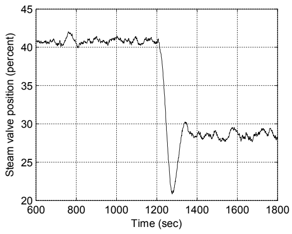
(a) Measured level with disturbance rejected



(b) Measured temperature with disturbance rejected



(c) Cold water valve position

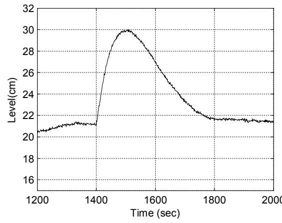


(d) Steam valve position

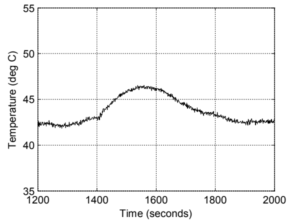
Fig. 9. Regulatory control of level and temperature using cascaded PID controller

hot water is considered to be the disturbance. Thus, a change in hot water valve position means that a disturbance has appeared in the system. For the nominal operation condition, the hot water valve is kept fully closed. In order to observe the regulatory control action of the controller, the hot water valve position is changed from 0 percent to 4.76 percent. Thus, hot water acts as a disturbance to the system and causes a rise of both measured variables, level and temperature, from their defined set point. The controllers took action to bring back the measured variable to the initial set point.

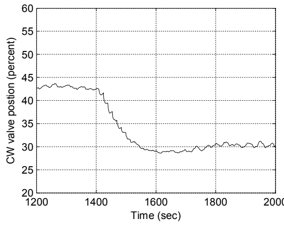
Figures 9 through 11 show the measured outputs and actuator movements after a disturbance is introduced into the system. From these results it is clear that all the controllers are capable of bringing the process to its initial state. A cascaded PID controller gives the fastest disturbance rejection with an undershoot and it has significant large swing in the actuator, which is not desirable. Both DMC-PID and PID-free structures reject disturbance without any undershoot. In the case of the actuator movement hybrid structure has less variation. However, the hybrid structure is significantly slower than the PID-free structure in disturbance rejection



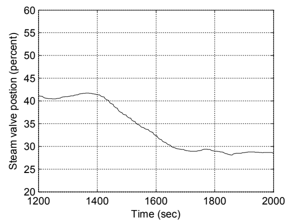
(a) Measured level with disturbance rejected



(b) Measured temperature with disturbance rejected

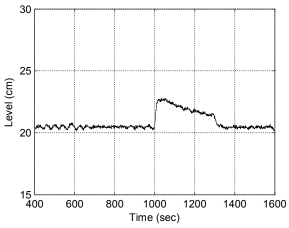


(c) Cold water valve position

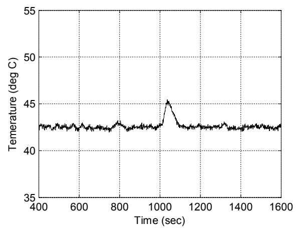


(d) Steam valve position

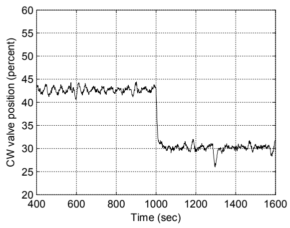
Fig. 10. Regulatory control of level and temperature using hybrid DMC-PID controller



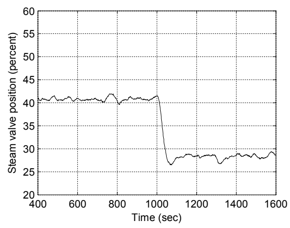
(a) Measured level with disturbance rejected



(b) Measured temperature with disturbance rejected



(c) Cold water valve position



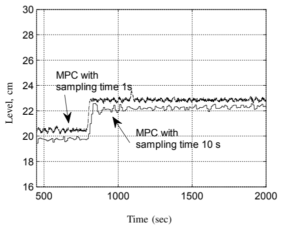
(d) Steam valve position

Fig. 11. Regulatory control of level and temperature using PID-free DMC controller

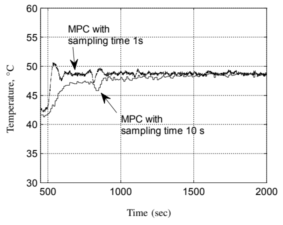
and allows a bigger rise of the measured output compared to the PID-free structure. The performance of hybrid structure may be improved by increasing the execution frequency of the supervisory DMC.

VI. Effect of Execution Frequencies in PID-free DMC Performance

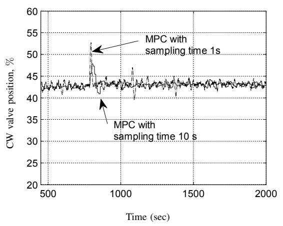
Performance comparison in the previous section convincingly demonstrates that PID-free DMC structure has a superior performance over cascaded PID or DMC cascaded to PID structure. However, the main concern for the PID-free DMC is that it has significantly more computational load, as DMC has to provide a control action at every second. Decreasing the execution frequency would help to decrease



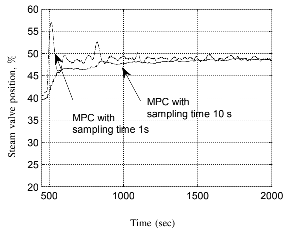
(a) Measured level with with two different execution frequency



(b) Measured temperature with two different execution frequency



(c) Cold water valve position



(d) Steam valve position

Fig. 12. Set-point tracking performance comparison of PID-free MPC structure for different execution frequencies

the computational load. Moreover, PID-free DMC has more fluctuation in the valve position, which can be reduced by increasing sampling time, hence decreasing execution frequency. In this section, PID-free DMC is implemented at two different frequencies and their performances are evaluated. The first one is the controller described in the previous section with a sampling time of 1s, while for the other, a sampling time of 10s is chosen. Set point tracking performances of the PID-free DMC at these two execution frequencies are observed. The set point of level is changed from 20.5 to 22.85 cm at t= 800s and the set point of the temperature is changed from 42.5°C to 48.73°C at t= 500s.

Figure 12 shows the measured outputs and actuator movements at different execution frequencies. Comparing the results, we see that, for the lower execution frequency, a steady state error exists between the set-point and the response for a prolonged period. However, the valve movement is significantly reduced for the lower execution frequency. All these phenomena should be taken into account while choosing an execution frequency of a DMC controller.

This simulation is carried out in different execution frequencies for understanding the behavior of DMC while execution frequency is changed. This is mentioned in the paper that, when sampling time is used 10s instead of 1s, movement of valve and overshoot of process variable are reduced. However, this reduction comes at the cost of higher settling time to track the reference. So, while performing a PID free DMC, execution frequency should be chosen based on the pros and cons of the too high and too low execution frequency.

VII. Conclusion and Future work

A comprehensive simulation-based study was carried out to compare the performances of the three control structures: Cascaded PID,'DMC cascaded to PID' and a 'PID-free DMC', where DMC is directly manipulating the actuators. The simulation study was carried out on a CSTH system. The performance of the controllers for set point tracking and disturbance rejection were monitored. ISE is used as the control performance indicator which clearly suggests PID-free DMC structure has the best performance. However, PID-free MPC needs to be executed at a high frequency which increases the computational load.

The effectiveness of the methodologies are discussed in this study based on the simulation results. This can be further validated using an experimental study. The effect of valve non-linearity on the performance of the PID-free MPC structure was not studied. This is an important question which can be studied using an experimental set up.

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