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Design a Model Predictive Controller for an Electrical Furnace System

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ABSTRACT

The purpose of this paper is to design a model predictive controller (MPC) to improve the performance of electric furnace system to the desired requirements. The presence of delay in the system especially, the long delays makes analysis and control design much more complex. Unlike time delay compensation methods, the predictions are made for more than one time delay ahead in the MPC since the Future values of output variables are predicted using a dynamic model of the system and current measurements. From the analyzed and compared results it is noticed that the system response with MPC shows high tracking performance in transient and steady state.

Keywords: Electric Furnace, Model Predictive Controller, Time Delay, Pade Approximation.

تصميم مسيطر تنبؤي نموذجي لنظام فرن كهربائي

الخلاصة

إنّ غرضَ هذا البحث هو تصميم جهاز سيطرة تنبؤي نموذجي (Model Predictive Controller) لتَحسين أداءِ نظامِ الفرنِ الكهربائيِ إلى المتطلباتِ المطلوبةِ. وجود التأخيرِ في النظامِ خصوصاً التأخيرات الطويلةَ يجْعلُ عمليةَ التحليلَ والتصميم والسيطرةَ عليها أكثر تعقيداً. على خلاف طرقِ تعويضِ تأخيرِ الوقتِ، التنبؤات تحدث لأكثر مِنْ تأخير سابق مقدما في جهاز السيطرة التنبؤي النموذجي لكون القِيَمِ المستقبليةِ لمتغيّراتِ الناتجِ يتم التنبؤ بها بالاعتماد على النموذج الديناميكي(Dynamic Model) للنظام والمقاييسِ الحاليةِ. من تحليل ومقارنة النتائج لوحظ بأنّ استجابة النظامَ بأداء عالي مع جهاز السيطرة التنبؤي النموذجي في الحالةِ العابرةِ والثابتةِ.

INTRODUCTION

Furnaces are thermal devices with a relatively large time delay in their response. Time delay is the property of a physical system by which the response to an applied action is delayed in its effect. The presence of long delays makes system

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analysis and control design much more complex. What is worse is that some delays are too long to perceive and the system is misperceived as one without delays. The conventional PID controllers are commonly used in automation. PID controllers do not meet all the requirements of high-quality control. In spite of this, several researches have been done in this field . A brief description of these researches is submitted in the following paragraph. In [1], the Fuzzy-PID controller is designed where The composite Fuzzy-PID controller can obtain ideal dynamic response of temperature control such as small overshoot. In [2], a dynamic model of a walking beam billet reheating furnace is constructed. The model is based on a multilayer perception neural network, which is trained using a sequential window batch learning algorithm. The model is constructed on the basis of a multilayer perception neural network with three layers. In order to make the model be suitable for the dynamics of furnace and rapidity for online using. In [3], the PID control method based on fractional-order model was used at the same time, integer order controllers based on both fractional-order model and integer order model are designed and simulation study is done. In [4], a method of reheating furnace temperature PID controller parameters self-setting based on

Mind Evolutionary Algorithm (MEA) and Fuzzy Neural Network (FNN) had been proposed. It is essay to deal with parameter adjusting in heating furnace PID controller by combining MEA and FNN. In [5], the different methods of PID controller design are used for different types of continuous systems. The Graphical User Interface (GUI) is used for educational purposes in subjects which the basics of automatic control are introduced. This paper intended to design a MPC because it is proved a very efficient performance in dealing with such systems where it is originally developed to meet the specialized control needs of power plants and several industrial sectors. The general design objective of model predictive control is to compute a trajectory of a future manipulated variable u to optimize the future behavior of the plant output y. The optimization is performed within a limited time window by giving plant information at the start of the time window [6]. In MPC an optimal control problem has to be solved at each sampling instant. The basic idea of MPC can be seen in the following analogy: “You are trying to walking across a street. First you look right and left to estimate if you safely can make it across the street. In other words, you are trying to predict if you can walk fast enough to make it across the street without getting hit by a car. You come to the conclusion that it is safe and start walking. Then something unforeseen happens, a car comes towards you with great speed. You then have to make a new decision, to either walk back to the sidewalk, or to increase your speed to make it across the street” [7]. MPC is suitable for almost any kind of problem; it displays its main strength when applied to problems with [8]:

♦ A large number of manipulated and controlled variables.

♦ Constraints imposed on both the manipulated and controlled variables.

♦ Changing control objectives and/or equipment (sensor/actuator) failure.

♦ Time delays, Processes are difficult to control with standard PID algorithm (e.g., large time constants, substantial time delays, inverse response, etc.

♦ There is significant process interactions between u and y. i.e., more than one manipulated variable has a significant effect on an important process variable.

♦ Constraints (limits) on process variables and manipulated variables are important for normal control.

The paper is organized as follows: Section 2 shows the Pade approximation of time delay Section 3 presents the model of electric furnace system. In section 4 The Model Predictive Controller design is presented. Finally the simulation results discussed in section 5.

PADE APPROXIMATION OF A TIME DELAY

An asymptotic expansion or a Taylor expansion can often be accelerated quite dramatically or even turned from divergent to convergent. Pade approximates time delays by rational models. Such approximations are useful to model time delay effects such as transport and computation delays within the context of continuous-time systems. The Laplace transform of a time delay of T_d seconds is exp($-sT_d$). This exponential transfer function is approximated by a rational transfer function using Pade approximation formula [9].

$$e^{-T_d s} \approx \frac{1 - k_1 s + k_2 s^2 + \cdots \pm k_n s^n}{1 + k_1 s + k_2 s^2 + \cdots + k_n s^n} \qquad \dots (1)$$

Where, n is the order of the approximation and the coefficients k_i are functions of n. The pade approximations are based on a minimization of the truncation errors in a finite series expansion of exp ($-sT_d$). Table (1) shows, as an illustration, the k-values for the orders n = 1 and n = 2.

Table (1) Pade approximations Coefficients of order n = 1 and n = 2 [9].

n=1	n=2
$k_1=\frac{T_d}{2}$,other k_i=0	$k_1=\frac{T_d}{2}$, $k_2=\frac{T_d^2}{12}$,other k_i=0

The syntax of Pade-function in MATLAB is shown in the following expression:

[Numerator, Denominator] = pade (T_d, n) … (2)

The Pade approximation of order **n** of the continuous-time delay is exp ($-sT_d$) in transfer function form. The row vectors contain the numerator and denominator coefficients in descending powers of ***s***. Both are nth-order polynomial. It is worth mentioning that the high-order Pade approximations produce transfer functions with clustered poles as shown in equations (3,4,5) for 1st ,2nd and 5th order respectively. Because such pole configurations tend to be very sensitive to perturbations, Pade approximations with high order should be avoided. Figure 1 shows the step response of the Pade approximation and the exact time-delay (5 second). For comparison also the step response. It is seen that the Pade approximations gives inaccurate expression for the time-delay, so it should be used only if it cannot be used the exact transfer function $e^{-T_a s}$ in the calculations [9].

$$\frac{-s+0.4}{+s+0.4} \qquad \dots (3)$$

$$\frac{s^2-1.2s+0.48}{s^2+1.2s+0.48} \qquad \dots (4)$$

$$\frac{-s^5+6s^4-16.8s^3+26.88s^2-24.19s+9.677}{+s^5+6s^4+16.8s^3+26.88s^2+24.19s+9.677} \qquad \dots (5)$$

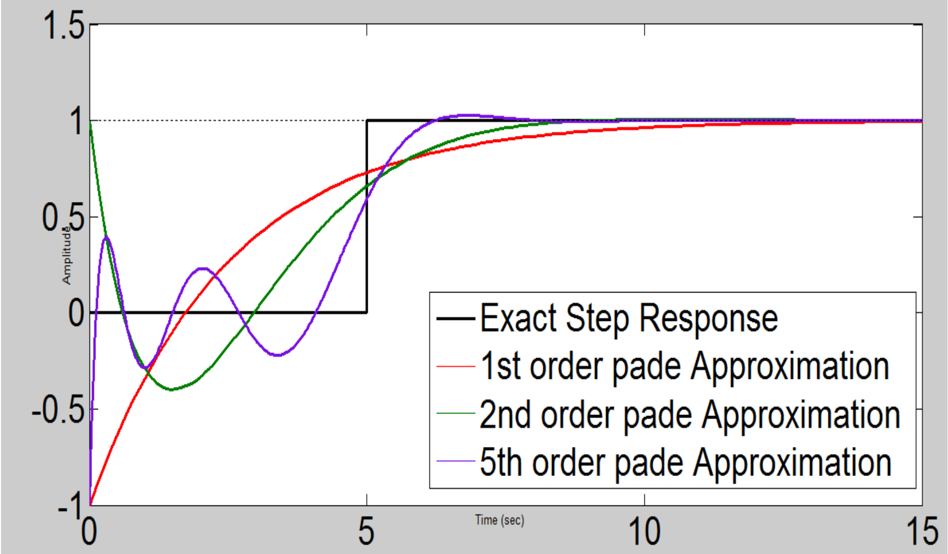


Figure (1) Step Response for Pade Approximation of a time delay of 5 sec.

ELECTRICAL FURNACE MODEL

Electric furnace is used for heating purposes in many industrial production processes. Electric furnaces are used when required precise control of temperature. There are three types of electric furnaces, they are as follows: (1) induction heating furnace (2) resistance heating furnace and (3) arc furnace depending on the method of heat generation [10]. The resistance heating furnace is used in this work. In resistance heating furnaces, the resistance heating elements are used to generate the heat in a furnace. The electric furnace temperature control is checked by the designed controller, manipulating changes of power requirement. The actual temperature is sensed, whereby the control algorithm modulates the furnace power requirement. Block diagram of electric furnace control is shown in Figure (2). The Model of electrical furnace is described by the following transfer function as delayed second order system [4,5]:

$$G(s) = \frac{K\,e^{-T_d s}}{(T_1\,s+1)(T_2\,s+1)} \qquad \dots (6)$$

Where, it is assumed the following system parameters:

K=0.87 →static gain
$T_1=T_2=200$ sec →time constant
$T_{d=5\ \mathrm{sec}}$ →time delay

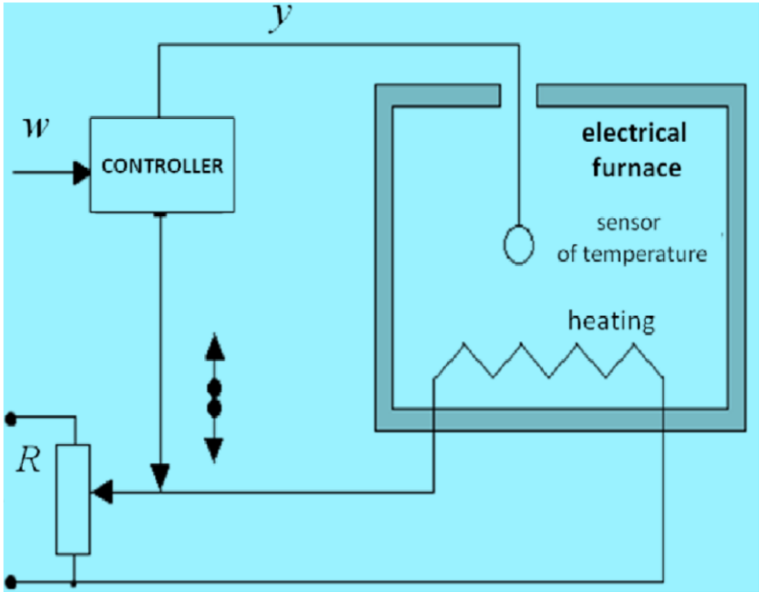


Figure (2) Electric Furnace Control [5].

The time delay transfer function is:

$$H(s) = e^{-T_d s} \qquad \dots (7)$$

As a time delay, the most common approximation is the first order Pade approximation [6]:

$$e^{-T_d s} \approx \frac{1-\frac{T_d}{2}s}{1+\frac{T_d}{2}s} = \frac{1-2.5S}{1+2.5S} \qquad \dots (8)$$

With the approximation of the time delay the overall transfer function of the system becomes:

$$G(s) = \frac{K}{(T_1\,s+1)(T_2\,s+1)}\,\frac{(1-\frac{T_d}{2}s)}{(1+\frac{T_d}{2}s)} \qquad \dots (9)$$

MODEL PREDICTIVE CONTROLLER

In Model Predictive Control (MPC) an optimal control problem has to be solved at each sampling instant. MPC has attracted notable attention in control of dynamic systems and has gained the important role in control practice [11, 12]. The MPC can be summarized as follows:

- Predict the future behavior of the process state/output over the finite time horizon.
- Compute the future input signals on line at each step by minimizing a cost function under inequality constraints on the manipulated (control) and/or controlled variables.
- Apply on the controlled plant only the first of vector control variable and repeat the previous step with new measured input/state/output variables. Therefore, the presence of the plant model is a necessary condition for the development of the predictive control. The success of MPC depends on the degree of precision of the plant Model.

4.1 Optimization in MPC

The MPC control law can be most easily derived by referring to the Figure (3). For any assumed set of present and future control moves $\Delta u(k)$, $\Delta u(k+1)$, $\Delta u(k+M-1)$, where the vector Δu Often called decision variable in the optimization literature. Since Developed predictive control problem and solved within the framework of the receding horizon control and taken into account the limitations of each Moving horizon window [8]. It allows changing the restrictions at the beginning of every window optimization, and also gives us a way to address the restricted control problem numerically. The future behavior of the **system outputs** $y(k+1|k)$, $y(k+2|k)$, . . . , $y(k+P|k)$ can be predicted over a **prediction horizon** ($P=20$). The ($M=4$) present the **control horizon or control moves** and ($M \le P$). In order to calculate the optimal controlled output sequence (the output that tracks optimally a reference trajectory). The manipulated variables, u(k), at the k-th sampling instant are calculated so that they minimize an objective function, J. For Example: Minimize the sum of the squares of the deviations between predicted future outputs and specific reference trajectory. As shown in the following form:

$$J = \sum_{l=1}^{P} \left\| \Gamma_l^y [y(k+l \mid k) - r(k+l)] \right\|^2 + \sum_{l=1}^{M} \left\| \Gamma_l^u [\Delta u(k+l-1] \right\|^2 \qquad \ldots(10)$$

Where:

- Γ_l^y and Γ_l^u are weighting matrices used to penalize particular components of output and input signals respectively, at certain future intervals.

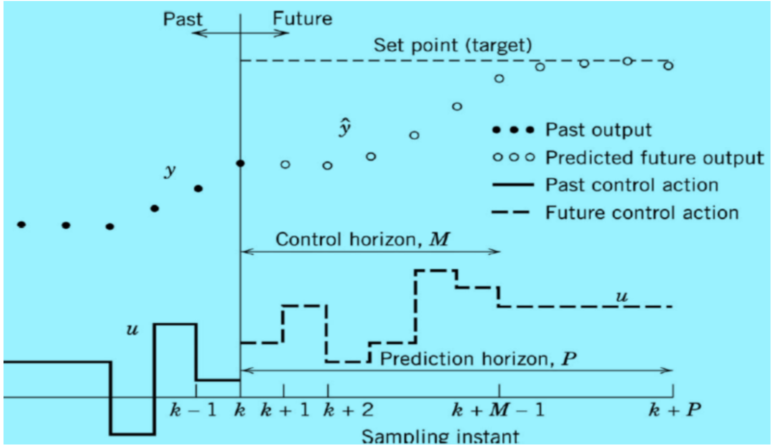


Figure (3) Model Predictive Controller [8].

Calculations of MPC

The control calculations are based on both future predictions and current measurements as shown in Figure (3).

1. At the *k*-th sampling instant, the values of the manipulated variables, ***u,*** at the next *M* sampling instants, {***u***(k), ***u***(k+1),.., ***u***(*k*+*M* -1)} are calculated. This set of *M* is calculated so as to minimize the predicted deviations from the reference trajectory over the next *P* sampling instants while satisfying the constraints.
2. Then the first “control move”, ***u***(*k*), is implemented.
3. At the next sampling instant, *k*+1, the *M*-step control policy is re-calculated for the next *M* sampling instants, *k*+1 to *k*+*M,* and implement the first control move, ***u***(*k*+1).
4. Then Steps 1 and 2 are repeated for subsequent sampling instants.

MPC with Furnace System

The block diagram of the controlled system is shown in Figure (4) below. The block of MPC is described in Appendix A.

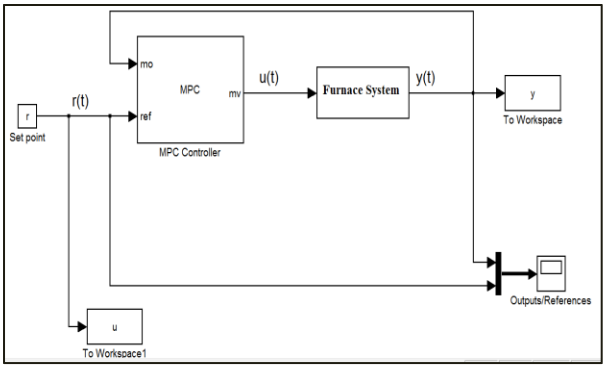
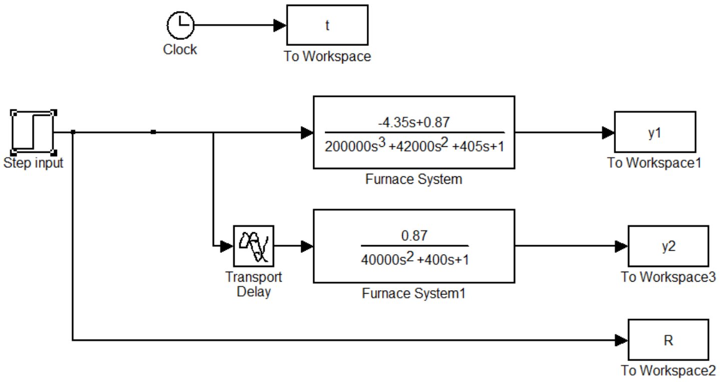


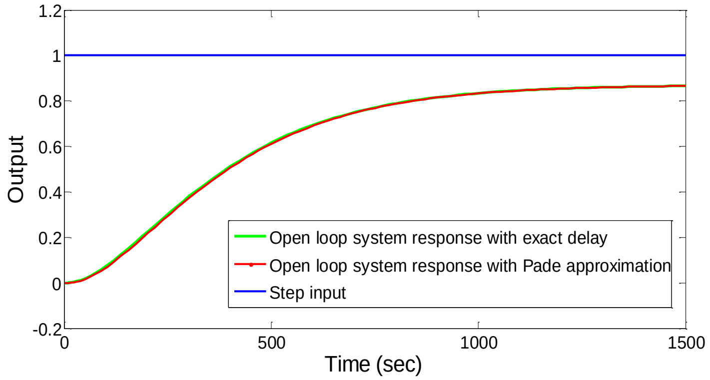
Figure (4) Block Diagram of Furnace System With MPC Controller.

SIMULATION RESULTS

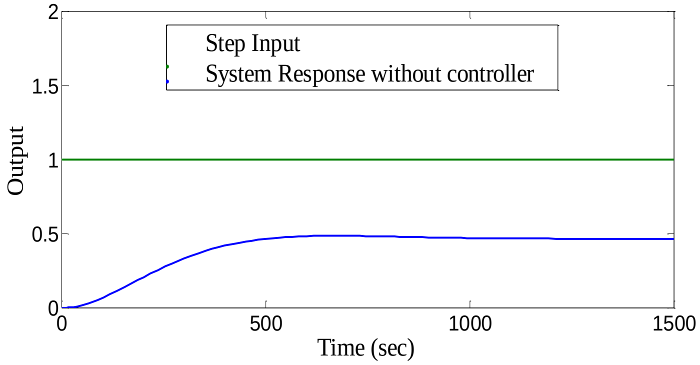
The analytic results are obtained by using MATLAB 2010a (M-file and Simulink). First, it is needed to compare the effect of delay approximation on the system response. So it applied the exact and Pade approximation on the open loop furnace system as shown in Figure (5). From the response in Figure (6) it can conclude that the difference between the exact delay and Pade approximation is obviously very slight. Then the simulaition is done for closed loop without controller (with unity feedback) as shown in Figure (7), where it is shown that the system without controller is slow down and unable to track the desired level of the temperature. In order to eleminate the steady state error and to get better tracking performance a PID controller is applied. As shown in Figures (8,9). The PID controller parameters are selected by PID tuning tool in MATLAB. Since the PID Tuner provides a fast and widely applicable single-loop PID tuning method. With this method, the PID can tune parameters to get best performance in the system time response. The system response with PID controller has the ability to get the desired level with acceptable performance but the system speed still slow with peak overshot. To enhance the system response a model predictive controller is designed . As shown in Figure (10), the rising time, settling time and error steady state are reduced and the Peak Overshoot is eliminated. Figure (11) shows the powerful of MPC in tracking the required different temperatures comparing with PID controller. To show the powerful of the designed MPC controller, it applied different time delays as shown in Figure (12) and Figure (13) at the same controllers parameters. It noticed that when the delay is increased the system performance will be descended with PID controller while the system with MPC controller still Maintained the desired specifications as shown in Table(2).



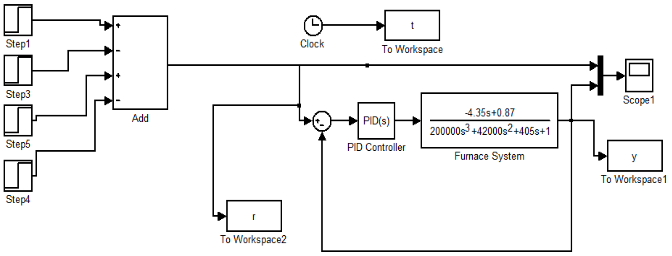
Figure(5) Apply step input for the Furnace system with exact delay and Pade approximation.



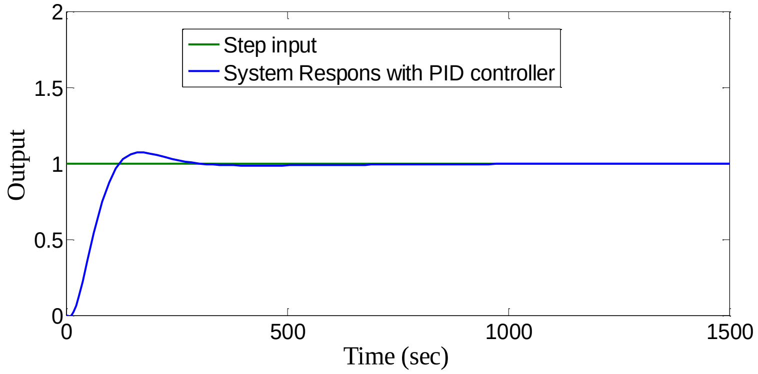
Figure(6) Open Loop Furnace System Response with Exact Delay and Pade Approximation .



Figure(7) Furnace System Response without Controller.



Figure(8) PID controller with the Furnace System.



Figure(9.a) Furnace System Response with PID Controller.

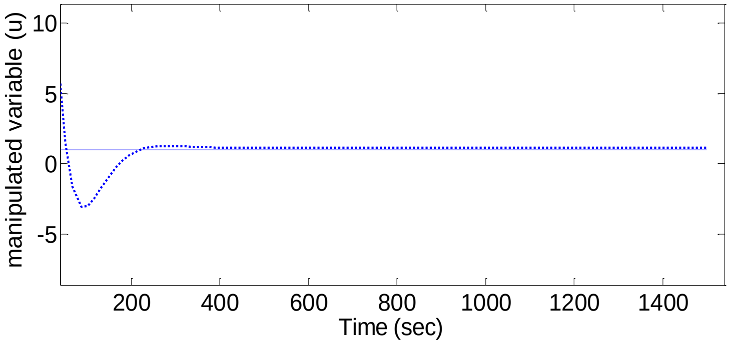
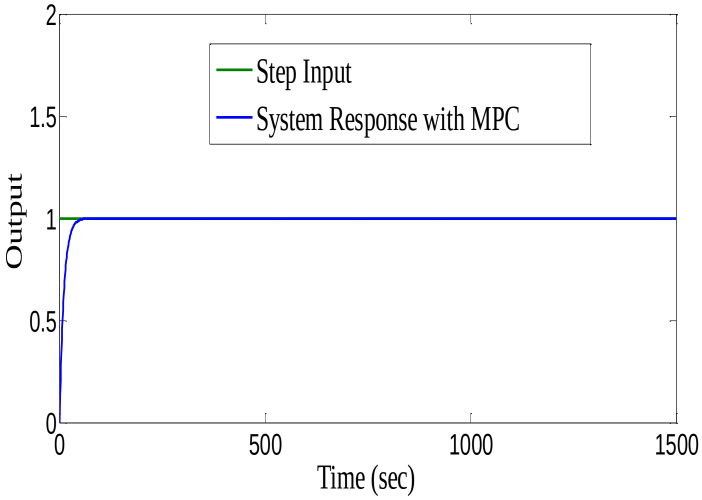


Figure (9.b) The response of the manipulated variable with PID controller.



Figure(10.a) System Response with MPC.

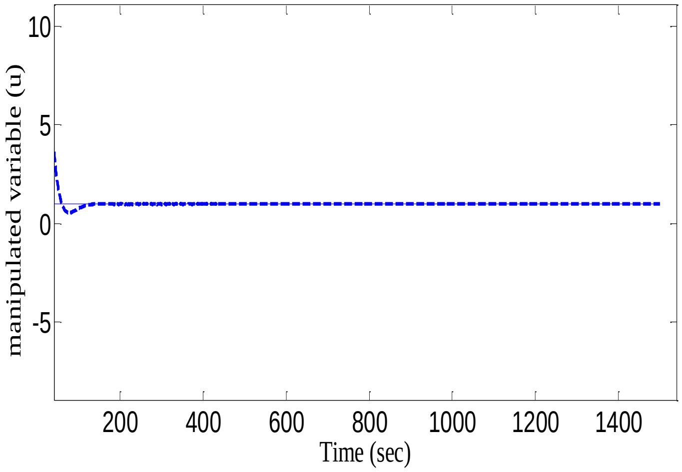
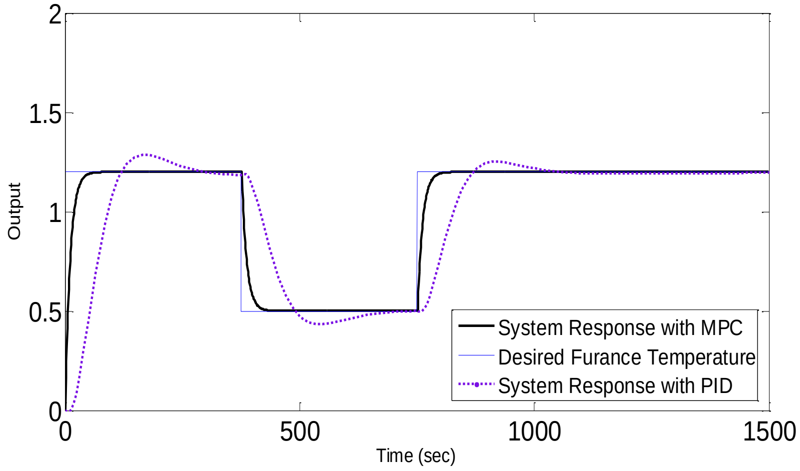
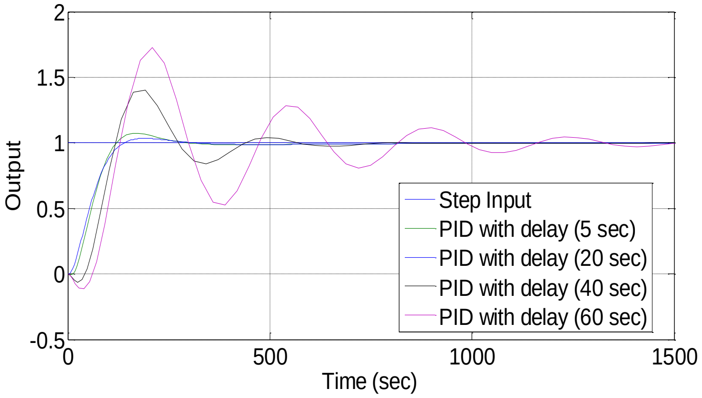


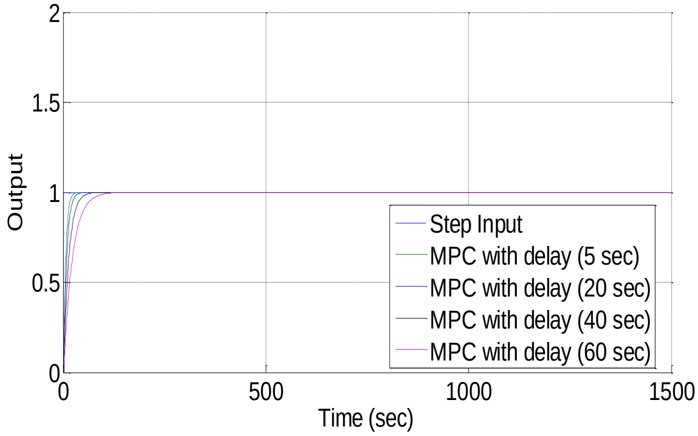
Figure (10.b) The response of the manipulated variable with MPC.



Figure(11) Furnace System Response with MPC and PID Controller for variable Furnace Temperature.



Figure(12) Furnace System Response with PID contrroller under different time delays.



Figure(13) Furnace System Response with MPC under different delays time.

Table (2) Time Response Specifications Comparison.

Controller	Time Delay (sec)	Rise time, t_r(sec)	Peak overshoot, M_p %	Settling time t_s(sec)
PID	5	121.45	7.1	300
PID	20	140	3.4	315
PID	40	118	40.3	800
PID	60	130	72.9	1400
MPC	5	42	-	45
MPC	20	58	-	60
MPC	40	85	-	90
MPC	60	128	-	150

CONCLUSIONS

In this paper the MPC has been designed to improve the performance of the electric furnace system. It can be conclude that, the MPC is a very powerful controller especially with the delayed systems. It performs a satisfactory step behavior and good set point tracking. It is shown that the time response specifications (rise time, settling time and peak overshoot) obtained by MPC are better than those obtained by PID controller. Finally, It is noticed that the manipulated variable achieved by MPC is smaller than that achieved by PID controller.

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APPENDIX A: Block Diagram of MPC

1. Model Predictive Control of a SISO Plant

The plant with SISO actually has multiple inputs, as shown in the Figure (A.1). In addition to the manipulated variable input, *u*, there may be a measured disturbance, *v*, and an unmeasured disturbance, *d*. The main objective is to hold a single *output*, $\bar{y}$, at a *reference value*, *r,* by adjusting a single *manipulated variable u*. This is generally termed a single-input single-output (*SISO)* plant. The block named MPC acts a Model Predictive Controller designed to implement the control objective. It is worth mentioning that the controller is designed without apply any type of disturbance and noise on the furnace system, but it can use with other types of complex systems [8]. In the MPC, the Simulink Library has two blocks used to model MPC control in Simulink. Access the library either by using the Simulink Library Browser or by typing (mpclib) at the MATLAB command window as shown in the Figure (A.2).

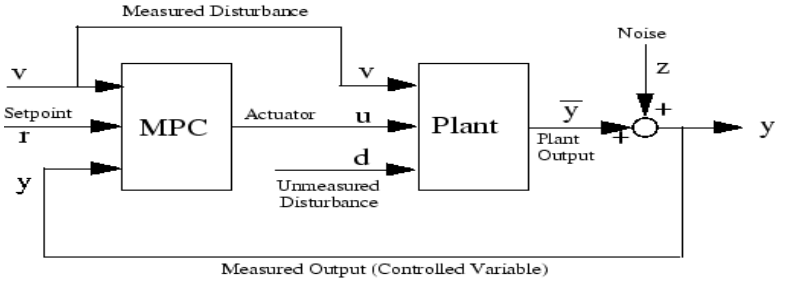
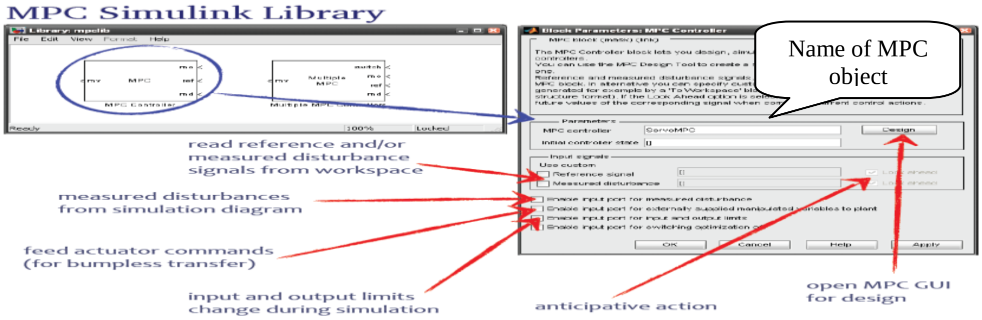


Figure (A.1) Block Diagram of a SISO Model Predictive Control.



The MPC Controller block lets you design, simu
controllers.
You can use the MPC Design Tool to create a
one.
Reference and measured disturbance signals
MPC block. In alternative you can specify cust
generated for example by a 'To Workspace' blo
structure format). If the Look Ahead option is sele
future values of the corresponding signal when com
rrent control actions.

Parameters

MPC controller: ServoMPC

Initial controller state: []

Input signals

Use custom

☐ Reference signal [] ☑ Look ahead

☐ Measured disturbance [] ☑ Look ahead

☐ Enable input port for measured disturbance

☐ Enable input port for externally supplied manipulated variables to plant

☐ Enable input port for input and output limits

☐ Enable input port for switching optimization c

Figure (A.2) MPC Simulink Library and Controller Block Mask.