A Modified Internal Model Control for Unstable – Time Delayed System

Basil Hamed, Walid Issa

Abstract*— *A new approach of control design of internal model controller is proposed in this paper. The proposed design method focuses on modifying the old* general *structure of IMC and develops a new model structure while saving the same general concept of using the invertible version of the system in the controller design. The new approach combines the IMC structure and the traditional structure of a control problem and this demonstrates an excellent performance and behavior against different disturbance inputs and model uncertainty presented in model parameter mismatch. Beside that a smith predictor is added to promote the design to compensate the delayed time systems. Also a proposed stabilizer has mentioned to deal with unstable systems.

Index Terms*— *IMC, Unstable, Time Delay, Pendulum System, Smith predictor.

I. INTRODUCTION

Open-loop unstable processes are difficult to achieve equilibrium state. Time delay always exists in the measurement loop or control loop, so it is more difficult to control this kind of process. Using routine control method can't acquire satisfying result [1].

Internal Model Control (IMC) is one of the advanced control strategies, which is of good robustness and is easy to design and tune. However, the routine IMC is not suit for unstable process or time delayed systems [2]. Scott A. Geddes has designed an IMC for time delay system [3]. However, it is not suitable for large time delay systems. According to Shang, and Wang, the design works well but not for nonlinear or unstable system [4]. Solving the problem of unstable system is by using a stabilizer beside IMC meanwhile the controller will become very complex [5, 6]. A modified IMC was proposed with tuning parameters [7]. However, the tuning problem was raised. The disadvantage of Kou Yamada [8] is the complexity of the structure and it does not guarantee the stability when a time delay is added. A proposed design of smith compensator using modified IMC for an unstable plant with time delay is presented [9]. However, this method demands a tuned parameters and an observer beside a PI controller that makes the overall system is complex. In this paper a new approach of IMC was proposed to solve the complexity of the old structure beside a smith predictor was added to compensate the time delay. In addition, a proposed method for unstable system was discussed to cover all design problems.

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II. MODIFIED IMC

The general structure of internal model control and its design procedure concentrate on getting the model of the process, reusing it as a reference model parallel to the process, and using it for design as shown in Figure 1. The realization process here requires a double work, one for the model and another for the controller. Because of the feedback in all cases occupying a position and hardware is implemented for the system. The proposed controller idea here is to reduce the amount of hardware used for realization and implementation without any additional component. The concept revolves around canceling the parallel reference model and uses the feedback as usual in the traditional control with some modification on the controller design.

Figure 2 illustrates the new structure of the modified IMC. It looks like the traditional control structure but the idea was focused on the controller design with reserving the concept of IMC.

The new proposed IMC structure cancel the repeated model appeared in the general IMC structure and presents a new $G_c(s)$ equation.

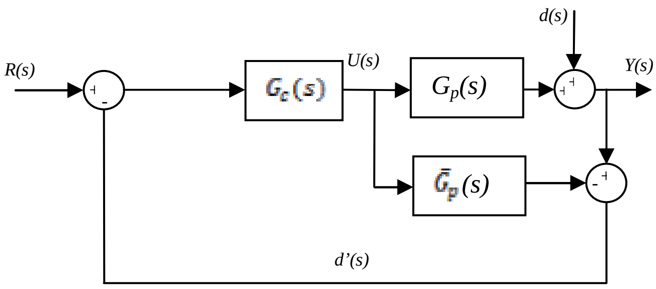


Figure 1: General Structure of IMC

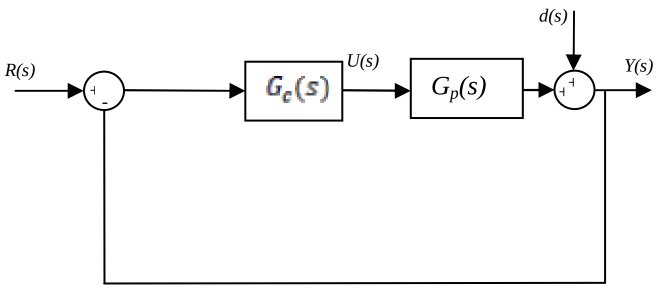


Figure 2: Modified IMC

The new proposed controller is to cancel the process model Gp(s) by the term Gp(s)-1 that considered as the inverse of the process transfer function and substitute it by different transfer function Gsc(s) such that:

$$G_c(s) = G_p(s)^{-1}.\ G_{sc}(s)$$

Where: Gsc(s) is the transfer function of the closed loop that will achieve the required criteria as shown in Figure 3.

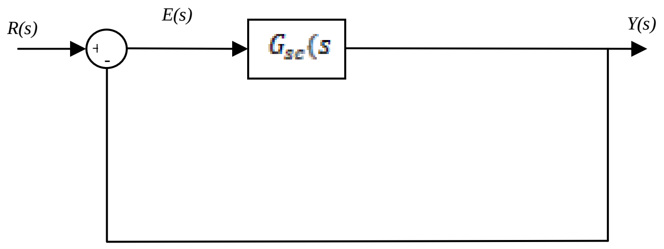


Figure 3: Controller Closed Loop System

The output of the system in Figure 3 is

$$Y(s) = \frac{G_{sc}(s)}{1+G_{sc}(s)} R(s) \qquad (1)$$

This will achieve the specifications required from the original system to be controlled.

The selection of $G_{sc}(s)$ is trivial and depends on $Y(s)/R(s)$ that can be assumed as a second order system that has the form of:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{(s^2 + 2\xi\omega_n s + \omega_n^2)} \qquad (2)$$

Where,

Percent overshoot $OS\% = e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}} \times 100$

Settling time $Ts = \frac{4}{\zeta\omega_n} = \frac{4}{\sigma}$

Peak time $Tp = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}}$

$G_{sc}(s)$ be can extract from equation (1) to get the form

$$G_{sc}(s) = \frac{Y(s)}{R(s) - Y(s)} \qquad (3)$$

Then have the overall system in Figure 2 and conclude that Gc(s) = Gp(s)-1. Gsc(s) will cancel the process behavior but will add Gsc(s) that guarantees the desired specification to be achieved.

To have the invertible form of the process faces some problems. To solve these problems is to use the method that split the process transfer function to invertible and non invertible parts then use the invertible part for design.

III. DESIGN PROCEDURE

The IMC design procedure consists of two main steps. The first step will insure that $G_c(s)$ is stable and causal; the second step will require $G_c(s)$ being proper. Let $\bar{G}_p(s)$ is a copy of $G_p(s)$.

Step1: Factor the mode $\bar{G}_p(s)$ into two parts:

$$\bar{G}_p(s) = \bar{G}_{p+}(s).\ \bar{G}_{p-}(s) \qquad (4)$$

$\bar{G}_{p+}(s)$ contains all Nonminimum Phase Elements in the plant model, that is all Right- Half-Plane (RHP) zeros and time delays. The factor $\bar{G}_{p-}(s)$, meanwhile, is Minimum Phase and invertible.

Then an IMC controller defined as

$$G_c(s) = \bar{G}_{p-}^{-1}(s) \qquad (5)$$

is stable and causal.

Step 2: Augment $G_{sc}(s)$ with $\bar{G}_{p-}^{-1}(s)$ such that the final IMC controller is now,

$$G_c(s) = \bar{G}_{p-}^{-1}(s).\ G_{sc}(s) \qquad (6)$$

As mention before; the selection of $G_{sc}(s)$ depends on the specification of the design.

IV. NUMERICAL EXAMPLE

A simple system represents a DC motor with a transfer function of:

$$G(s) = \frac{1.5}{S^2 + 14S + 40.02} \qquad (7)$$

The controller needs to achieve the design speciation: OS% < 10% and Ts < 5 sec.

First want to design Y(s) to meet the desired design:

$$\frac{Y(s)}{R(s)} = \frac{5.3}{(s^2 + 3s + 5.3)} \qquad (8)$$

Then obtain $G_{sc}(s)$ from $Y(s)$ such that $R(s)$ is impulse input

$$G_{sc}(s) = \frac{5.3}{s(s+3)} \qquad (9)$$

And when simulate $G_{sc}(s)$ as a closed loop system as shown in Figure 3 it is noted that the system will achieve the requirement as shown in Figure 4.

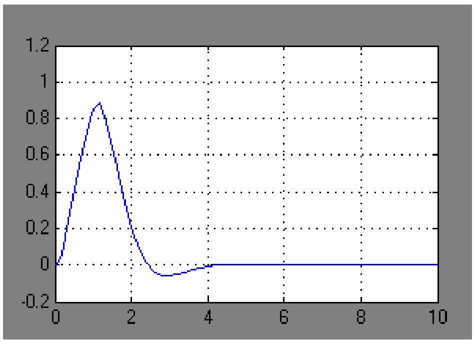


Figure 4: $G_{sc}(s)$ Closed Loop response

After applying the proposed controller

$$G_c(s) = G_p(s)^{-1} \cdot G_{sc}(s)$$

on the system as shown in Figure 5. The response will be the same response as shown in Figure 4 because the controller cancels the behavior of the process. Therefore, the controller can achieve the ideal desired response with systems that can be completely inverted.

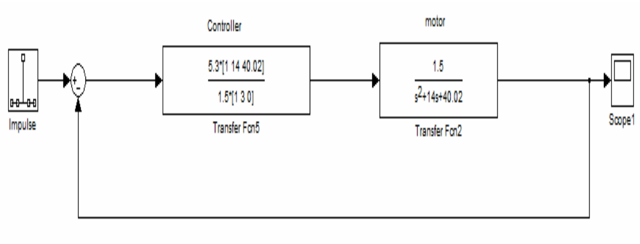


Figure 5: Overall Closed Loop System

V. MODIFIED IMC FOR TIME DELAYED SYSTEMS

For systems with time delay, modified IMC controller will not face any problem. Because of the controller design does not dependent on time delay value. In other words the controller structure is the same as time delay when varied because the time delay part is not invertible and will not be included in design. However, this type of controllers cannot compensate systems with long time delay. If the motor transfer functions has a time delay of 0.3 and 1 sec the result of simulation in Figure 6, and Figure 7 tell us that the time delay affect the response of the system by shifting it as the value of time delay. In addition, the response changed if it was compared with the ideal one in Figure 4 such that more overshoot and longer settling time. This result concludes us to; if the time delay is very long the system will be unstable and the response also will be unbounded. So it is difficult to obtain satisfactory performance of control systems with time delay, which is a well recognized problem in many control processes. The solution of this problem is represented by smith predictor.

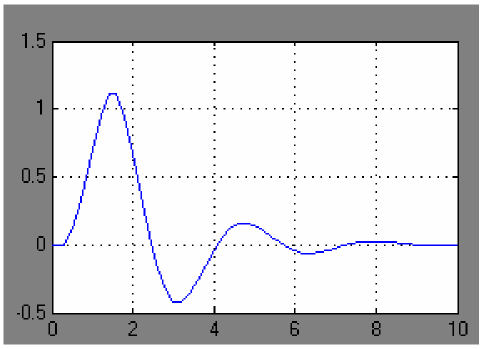


Figure 6: The Impulse Response for t = 0.3 sec

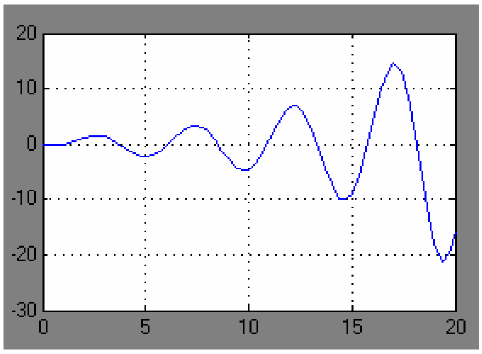


Figure 7: The Impulse Response for t = 1 sec

As known, the smith predictor compensates the time delay in the systems. After applying smith predictor, the system can be dealt as a delay free system.

To be more emphasis, consider the DC motor system presented in this paper. The system with smith predictor is shown in Figure 8. Its response is shown in Figure 9 which agrees with smith predictor.

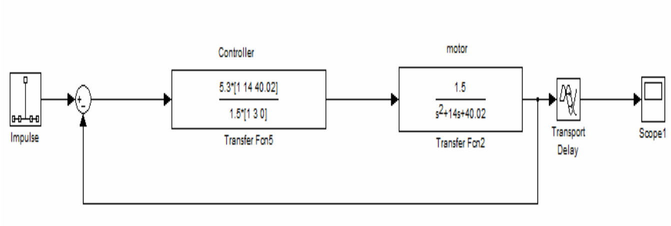


Figure 8: The system of DC motor with smith predictor

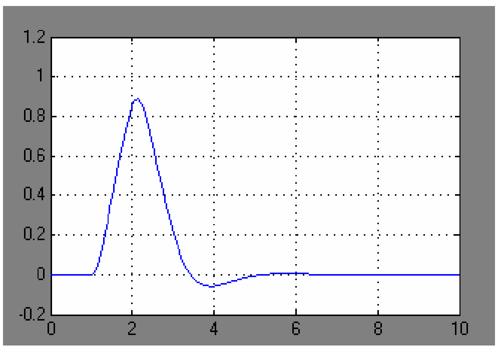


Figure 9: Result of DC motor system with smith predictor

VI. MODIFIED IMC FOR UNSTABLE SYSTEMS

The general rule of IMC based on is that the system to be controlled must be stable to apply the IMC controller. If the system is unstable, it should be stabilized before IMC controller is applied by any proportional controller or any other controllers. This rule is considered as a necessary condition to apply the modified IMC controller. Therefore, in all cases, need two controllers to handle unstable systems.

Consider the first order unstable system process with time delay of the form:

$$G_p(s) = \frac{k}{\tau s - 1} e^{-\theta s} \qquad (10)$$

Then choose a proportional controller K to stabilize this system as presented in Figure 10. K is intended to stabilize the delay free unstable model $\frac{k}{\tau s - 1}$, this simple proportional gain K will give a stable internal process

$$G_{ps}(s) = \frac{k}{\tau s - 1 + kK} \qquad (11)$$

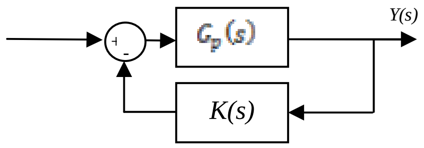
Clearly, $G_{ps}(s)$ is stable if $K > \frac{1}{k}$, then choose $K = \frac{2}{k}$ to make

$$G_{ps}(s) = \frac{k}{\tau s + 1} \qquad (12)$$

Then the delayed form will be

$$G_{ps}(s) = \frac{k}{\tau s + 1} e^{-\theta s} \qquad (13)$$

That can be handled with smith predictor to compensate the time delay and design a trivial controller.



a) Figure 10: Stabilizing unstable system

Another solution was proposed to solve the instability. Consider Figure 11 and let $G_p(s)$ is factorized in another way such that:

$$G_p(s) = \bar{G}_{un}(s).\bar{G}_s(s)$$

Where $\bar{G}_s(s)$ is a stable proper rational function and $\bar{G}_{un}(s)$ is bi-proper antistable and minimum phase function.

The term *antistable* refers to a system with all its poles in the open RHP and minimum phase refers to a system with all its zeros in the open LHP.

And let

$$Q(s) = \frac{1 + K(s)G_p(s)}{\bar{G}_{un}(s)} \qquad (14)$$

Where, K(s) is a stable stabilizing controller. So, the unstable poles of $1 + K(s)G_p(s)$ is identical to $G_p(s)$. Therefore Q(s) is stable. Then obtain that the dotted block is simplified to $\bar{G}_s(s)$ which is a stable rational system and the controller $G_c(s)$ can be designed easily.

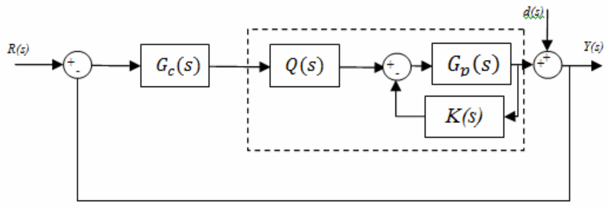


Figure 11: Modified IMC for Unstable systems

However, $\bar{G}_s(s)$ is a stable transfer function, it will contain unstable zeros so the inversion will make a problem. So in this case another factorizing is recommended as discussed in section 3 where

$$\bar{G}_s(s) = \bar{G}_{s+}(s).\bar{G}_{s-}(s)$$

And the controller then will consider the term $\bar{G}_{s-}(s)$ in its design.

I. Simulation & Results

The simulation will be held on the non-linear pendulum system to control its angle and to compare the traditional IMC with the modified IMC.

The pendulum can be modeled approximately as a linear second order system [10]:

$$G(s) = \frac{1}{1 + 0.0011s + 0.0264s^2} \qquad (15)$$

The controller transfer function of IMC is

$$C(s) = \frac{1 + 0.0011s + 0.0264s^2}{(0.04s + 1)(0.04s + 1)} \qquad (16)$$

The modified IMC controller is

$$C(s) = \frac{2000(1 + 0.0011s + 0.0264s^2)}{s^2 + 80s} \qquad (17)$$

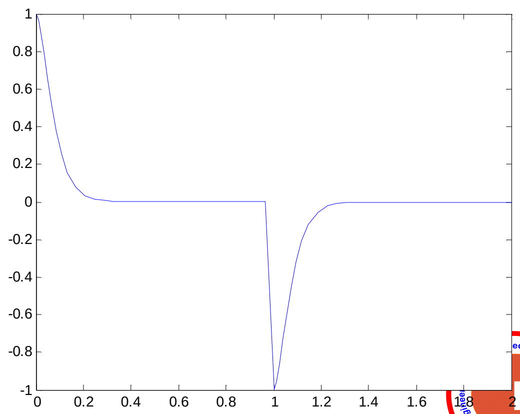


Figure 12: Impulse disturbance input response

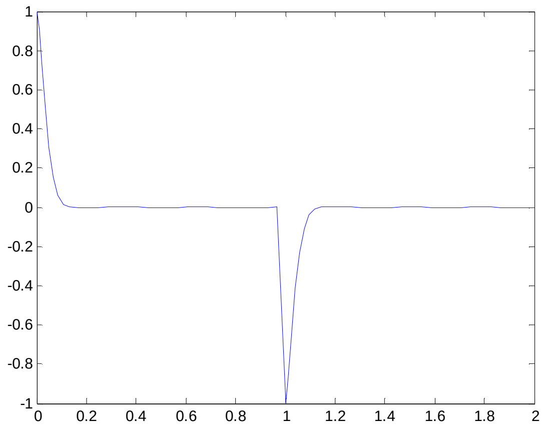


Figure 13: response of modified IMC

Figure 12 and Figure 13 illustrate the impulse responses of the pendulum system for the two controllers which show that the response of the modified IMC was quicker.

The pendulum system is a nonlinear system and its transfer function is a result of the linearization operation so the mismatch is present in all cases. So we will choose some parameters and vary their values in the model such that the plant and model transfer function are different.

$$G(s) = \frac{1}{1 + 0.0011s + 0.0264s^2} \qquad (18)$$

$$\tilde{G}_p(s) = \frac{1}{0.2 + 0.031s + 0.001s^2} \qquad (19)$$

Then the controller of IMC takes the form

$$C(s) = \frac{0.2 + 0.031s + 0.001s^2}{(0.04s + 1)(0.04s + 1)} \qquad (20)$$

The controller of modified IMC takes the form

$$C(s) = \frac{90000(0.2 + 0.031s + 0.001s^2)}{s^2 + 80s} \qquad (21)$$

The responses of the two techniques are displayed in Figures 16 and 17. The results are very clear to say that the modified IMC structure is now the best and overcome the mismatch and regulate its output to be zero against the traditional IMC structure, which behaves unstable, and the controller fails to regulate the output.

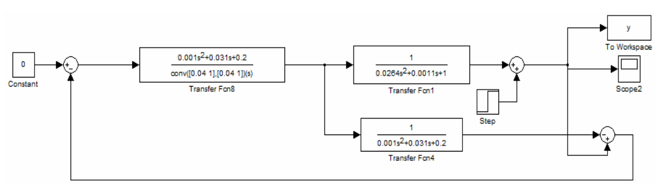


Figure 14: A plant/model mismatch of IMC system

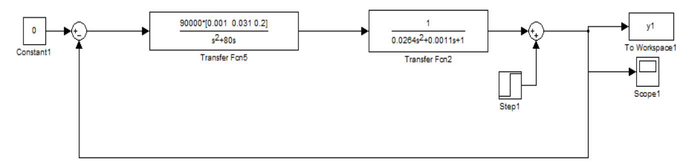


Figure 15: A plant/model mismatch of modified IMC system

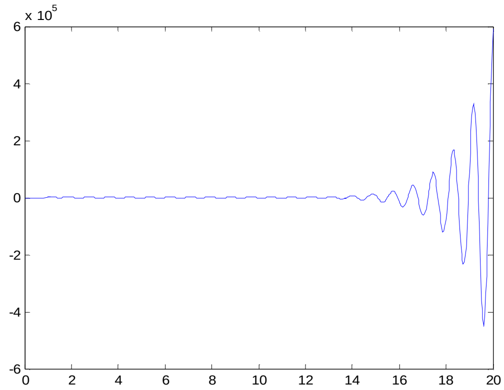
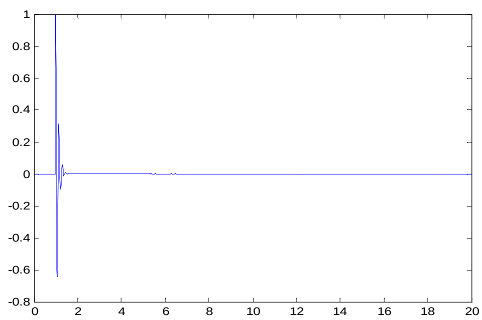


Figure 16: Response of IMC due to plant/model mismatch



b)

c) Figure 17: Response of modified IMC due to plant/model mismatch

The system seems that does not have time delay, but in many cases there is a time delay in almost all systems due to physical components characteristics and storage elements in the system although it might be very small.

Based on this, assume there is a small time delay in the pendulum system beside a mismatch in this delay between the plant and the model to make the competition worth.

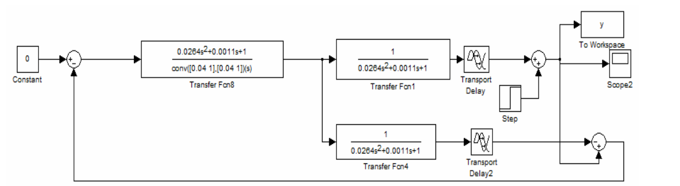


Figure 18: IMC structure with time delay mismatch

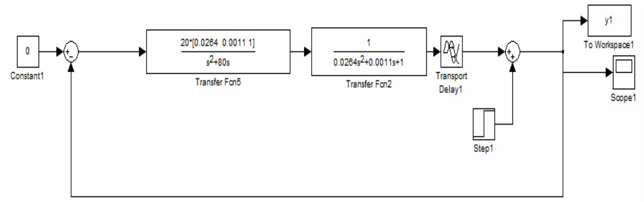


Figure 19: Modified IMC structure with time delay

In Figure 18 the system has a time delay for the plant t = 2 sec while its model has t=2.5 sec. Figure 19 has also t=2 sec delay for its system.

The time response of each system are shown in Figures 20 and Figure 21 and the responses showed the ability of modified IMC since it regulates the output and overcome the perturbation and save the stability. In the other hand, the traditional IMC lose the control and the response unbounded to finally yield to instability. The disadvantage of the modified IMC takes more time response and gets stability but this is forgiven when compared with the traditional one.

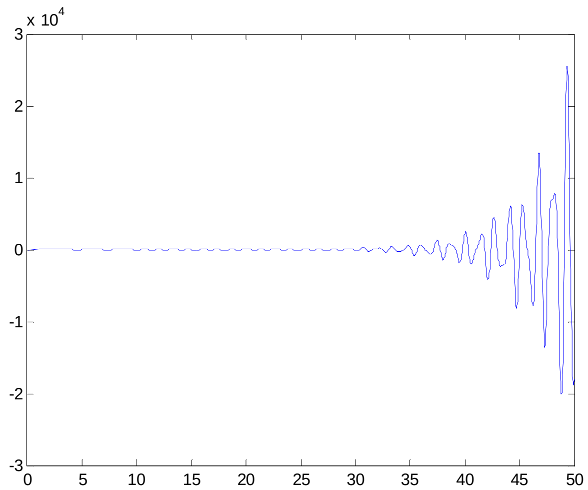


Figure 20: Response of IMC with a mismatch time-delayed system

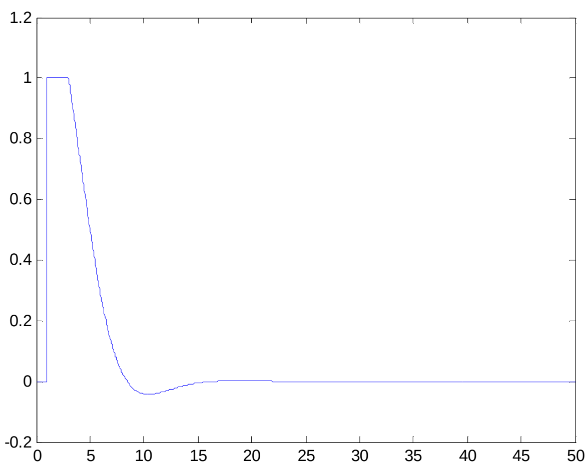


Figure 21: Response of a modified IMC time-delayed system

According to Shamsuzzohal and Lee, they compared the performance of the PID controller against IMC controller and the results indicate that the proposed IMC controller provides fast and smooth set-point response without a loss of disturbance performance [11].

In the same way, this part compares the results of the preceding results with the new approach result when applying it to the same system.

The transfer function of the system is:

$$G(s) = \frac{1e^{-3s}}{1 + 10s}$$

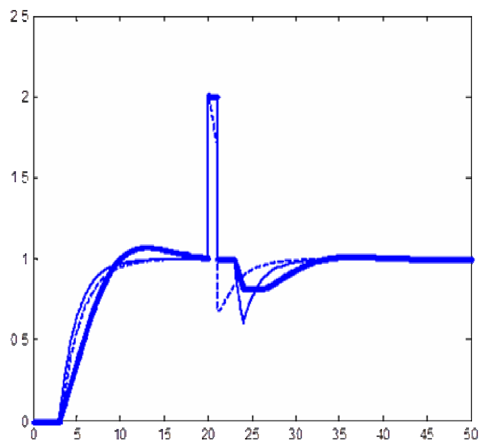


Figure 22: Response of both controllers to the proposed system

Figure 22 exhibit the results of three controllers. The solid line indicates the traditional IMC, the bold line for modified IMC without smith predictor, the dotted line for modified IMC with smith predictor.

Simulation results indicate that the response of the modified IMC with smith predictor is superior which compensate the time delay. The modified without smith predictor has a small overshoot but it needs a little smaller energy to eliminate disturbance than traditional IMC.

The traditional IMC suffer from a delay of 3 sec to compensate the disturbance and overshoot 50%. On the other side, the new method without SP has an overshoot of 20% but with SP it is 40% but without any delay.

II. Conclusion

In this paper, a new approach of control design of internal model controller was proposed. The proposed design method focuses on modifying the old general structure of IMC and develops a new model structure while saving the same general concept of using the invertible version of the system in the controller design. The new approach combines the IMC structure and the traditional structure of a control problem and this demonstrates an excellent performance and behavior against different disturbance inputs and model uncertainty presented in model parameter mismatch. Beside that a smith predictor is added to promote the design to compensate the delayed time systems. Also a proposed stabilizer has mentioned to deal with unstable systems.

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Eng. Walid Issa is a research Assistant August, 2010-Present at Electrical Engineering Department, Islamic University of Gaza (IUG) Palestine. Since 2007, he has Bachelor Degree in Electrical Engineering from IUG and received Master degree in 2011 from the same institute. He has worked as a teaching assistant in 2007 to 2010 in IUG and had an excellent experience of Microcontrollers, FPGA, Robotics, Power Electronics, Matlab and Labview.