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Ideal IMC Based PID Controller and its Design: A Review

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***Abstract*: Internal Model Control (IMC) refers to a systematic procedure for control system design based on the Q-parameterization concept that is the basis for many modern control techniques. What makes IMC particularly appealing is that it presents a methodology for designing Q-parameterized controllers that has both fundamental practical appeals. As a consequence, IMC has been a popular design procedure in the process industries, particularly as a means for tuning single loop, PID type controllers. In this paper we propose an optimum IMC filter to design an IMC-PID controller for better set-point tracking of unstable processes. The proposed controller works for different values of the filter tuning parameters to achieve the desired response. As the IMC approach is based on pole zero cancellation, methods which comprise IMC design principles result in a good set point responses. However, the IMC results in a long settling time for the load disturbances for lag dominant processes which are not desirable in the control industry.**

***Keywords*: Internal Model Control (IMC), Proportional Integral Derivative (PID), Q-parameters, Time Delay**

1. Introduction

The IMC design procedure design is quite extensive and diverse. It has been developed in many forms; these include single-input, single output (SISO) and multi-input, multi-output (MIMO) formulations, continuous-time and discrete-time design procedures, design procedures for unstable open-loop systems, combined feedback-feed forward IMC design, and so forth. Aside from controller design, IMC is helpful in assessing the fundamental requirements associated with feedback control, such as determining the effect of non-minimum phase elements (delay and Right-Half Plane (RHP) zeros) on achievable control performance. Since the sophistication of the IMC controller depends on the order of the model and control performance requirements, the IMC design procedure is also helpful in determining when simple feedback control structures (such as PID controllers) are adequate. IMC is a commonly used technique that provides a transparent mode for the design and tuning of various types of control. The ability of proportional-integral (PI) and proportional-integral-derivative (PID) controllers to meet most of the control objectives has led to their widespread acceptance in the control industry. The Internal Model Control (IMC)-based approach for controller design is one of them using IMC and its equivalent IMC based PID to be used in control applications in industries. IMC and IMC based PID controller to be used in industrial process control applications, there exists the optimum filter structure for each specific process model to give the best PID performance. For a given filter structure, as λ decreases, the inconsistency between the ideal and the PID controller increases while the nominal IMC performance improves [2].

2. IMC background

In process control, model based control systems are mainly used to get the desired set points and reject small external disturbances. The internal model control (IMC) design is based on the fact that control system contains some representation of the process to be controlled then a perfect control can be achieved. So, if the control architecture has been developed based on the exact model of the process then perfect control is mathematically possible.

Fig. 1. Open Loop Control Strategy [2]

Output = Qc* Gp * Set-point
Qc = controller Gp = actual process
Gp* = process model
Qc =inverse of Gp*
If Gp = Gp* (the model is the exactly same as the actual process)
Output is: Y(s) = Qc* Gp * Set-point
= (1/ Gp*)* Gp * Set-point
= Setpoint

3. Basic structure

The exceptional characteristic of IMC structure is including the process model which is in parallel with the actual process or the plant. Here '*' has been used to represent signals associated with the model.

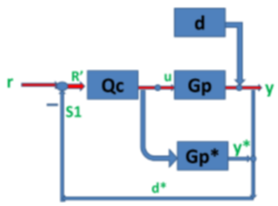

Fig. 2. Structure of IMC [2]

4. IMC parameters

The various parameters used in the IMC basic structure shown above are as follows:

Qc= IMC Gp= actual process
Gp*= process model
r= set point
r'= modified set point
u= manipulated variable (controller output)
d= disturbance
d*= calculated new disturbance
y= measured process output
y*= process model output
New calculated disturbance:
d*= (Gp - Gp*)u +d
Modified set-point or signal to the controller:
r'= r- d*= r- (Gp - Gp*) u – d

A model is perfect if process model is same as actual process, i.e. Gp=Gp*

And no disturbance means

d=0.

Thus we get a relationship between the set point r and the output y as

y = Gp.Qc .r

5. IMC Strategy

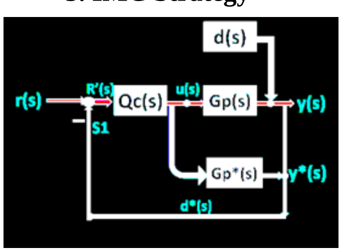

Fig. 3. IMC Strategy [3]

In the above figure, d(s) is the unknown disturbance affecting the system. The manipulated input u(s) is introduced to both the process and its model. The process output, y(s), is compared with the output of the model resulting in the signal d*(s). Hence the feedback signal send to the controller is

d*(s) = [Gp(s) – Gp*(s)].u(s) + d(s)

The error signal r'(s) comprises of the model mismatch and the disturbances which is send as modified set-point to the controller and is given by

r'(s) = r(s) – d*(s)

And output of the controller is the manipulated variable u(s) which is send to both the process and its model.

u(s) = r'(s) *Qc(s)
= [r(s) – d*(s)] Qc(s)
= [r(s)–{[Gp(s)–Gp*(s)].u(s)+d(s)}] . Qc(s)
u(s) = [[r(s)–d(s)]*Qc(s)] / [1+{Gp(s) – Gp*(s)} Qc(s)]

But y(s) = Gp(s) * u(s) + d(s)

Hence, closed loop transfer function for IMC is

y(s) = {Qc(s). Gp(s).r(s) + [1 – Qc(s) . Gp* (s)] .d(s)} / { 1 + [Gp(s) – Gp* (s)] Qc(s) }

Also to improve the robustness of the system the effect of model mismatch should be minimized. Since mismatch between the actual process and the model usually occurs at higher frequencies of the systems frequency response, a low pass filter f(s) is added to prevent the effects of mismatch. Thus the internal model controller is designed as inverse of the process model which is in series with the low pass filter i.e.

Q(s) = Qc(s)*f(s)

The order of the filter is chosen to make it proper or at least semi proper (such that order of numerator is equal to the order of denominator). The resulting closed loop then becomes

y(s) = {Q(s) . Gp(s) .r(s) + [1 – Q(s) . Gp* (s)] .d(s)} / { 1 + [Gp(s) – Gp* (s)] Q(s) }

6. Structure - (IMC)

Internal Model Control (IMC) forms the basis for the systematic control system design methodology that is the primary focus of this text. The first issue one needs to understand regarding IMC is the IMC structure (to be distinguished from the IMC design procedure). Figure 4(a) shown below is the "Internal Model Control" or "Q-parameterization" structure. The IMC structure and the classical feedback structure shown in Figure 4 (b) is its equivalent representation.

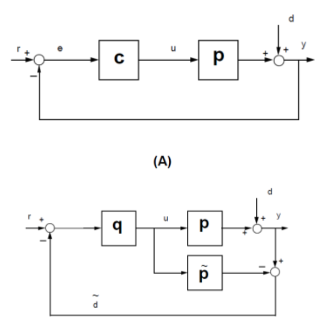

Fig. 4. (a) Q-Parameters, (b) Equivalent Representation [3]

Figure 4 (c) demonstrates the evolution of the IMC structure. We will show that the design of q(s) is more straightforward and intuitive than the design of c(s). Having designed q(s), its equivalent classical feedback controller c(s) can be readily obtained via algebraic transformations, and vice-versa [3].

$$c = \frac{q}{1 - q\hat{p}}$$
$$q = \frac{c}{1 + c\hat{p}}$$

For linear, stable plants in the absence of constraints on u, it makes no difference to implement the controller either through c or q.

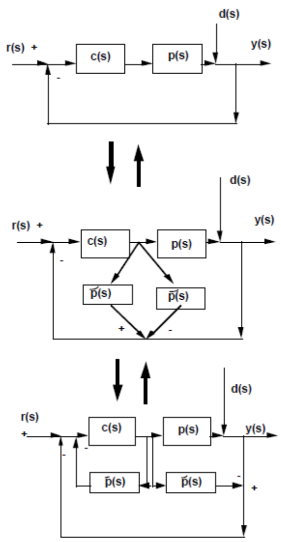

Fig. 4 (c) [3]

However in the presence of actuator constraints, one can use IMC structures to avoid stability problems arising from input saturation without the need for special anti-windup measures.

7. Closed-loop transfer functions for IMC

The sensitivity and ε and complementary sensitivity η operators define the closed-loop behavior of a classical feedback linear control system.

$$y = \eta r + \varepsilon d$$
$$u = p^{-1}\eta(r - d)$$
$$\boldsymbol{e}_c = \varepsilon(r - d)$$

We also know $\eta = pc(1 + pc)^{-1}$ for classical feedback control system. A statement of the sensitivity and complementary sensitivity operators in terms of the internal model $\hat{p}$ and the IMC controller q(s) corresponds to:

$$\eta(s) = \frac{pq}{1 + q(p - \hat{p})}$$
$$\varepsilon(s) = \frac{1 - \hat{p}q}{1 + q(p - \hat{p})}$$

In the absence of model mismatch ($p=\hat{p}$), these functions simplify to

$$\hat{\eta}(s) = \hat{p}q$$
$$\hat{\varepsilon}(s) = 1 - \hat{\eta}(s) = 1 - \hat{p}q$$
$$\hat{p}^{-1}\hat{\eta} = q$$

Which lead to the following expressions for the input/output relationships between y, u, e_c, r and d:

$$y = \hat{p}qr - (1 - \hat{p}q)d$$
$$u = q(r - d)$$
$$e_c = (1 - \hat{p}q)(r - d)$$

From the above equations we are able to recognize the benefits of the IMC parameterization. The closed-loop response between set-point r and output y is readily determined from the properties of the simple product $\hat{p}q$. Furthermore, the manipulated variable response is determined through the design of q. As a consequence, both analysis and synthesis tasks in the control system are simplified [4].

8. Internal stability

Internal Stability (IS) is a critical theoretical requirement for any control system. In an internally stable control system, bounded input signals introduced anywhere in the control system result in bounded output signals everywhere in the control system. For the IMC structure we have the following important internal stability results:

- Assume a perfect internal model ($p=\hat{p}$). The IMC control system is internally stable if and only if both p and q are stable.
- Assume that p is stable and $p=\hat{p}$, then the classical feedback system is Internally Stable if and only if q is stable.

These results apply for the IMC structure even if $\hat{p}$ and q are nonlinear operators. For the case of an open-loop, linear stable system under no plant model mismatch, the IMC structure thus offers the following benefits with respect to classical feedback:

- It eliminates the need to solve for the roots of the characteristic polynomial 1+pc; stability can be determined by examining only the poles of q.
- It is possible to search for q instead of c without any loss of generality.

9. IMC based PID structure

In the IMC structure the point of comparison between the process and the model output can be moved as shown in the figure below to form a standard feedback structure which is nothing but another equivalent feedback form of IMC structure know n as IMC based PID structure.[5,6].

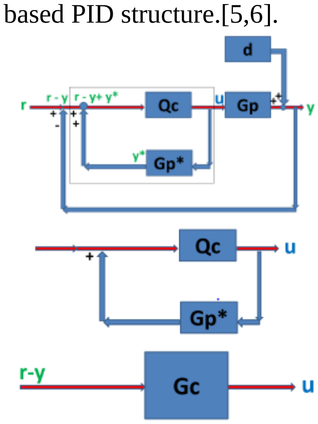

Fig. 5. IMC and IMC based PID structure

10. Comparison with standard PID controller

Now we compare with PID Controller transfer function. For first order:

Gc(s) = [Kc . (Ti .s + 1)]/ (Ti. s)]
And we find that Kc and Ti (PI tuning parameters)
Kc=Tp/(lem*Kp); Ti= Tp
Similarly for 2nd order we compare with the standard PID controller transfer function given by:[7,8]
Gc(s) = Kc.[(Ti . Td .s^2+Ti . s+1)/Ti . s].[1/ Tf . s+1]
Where, T = Tau (constant);
Ti = integral time constant;
Td = derivative time constant;
Tf = filter tuning factor Kc = controller gain

11. Simulation for IMC based PID 1st order system and comparison with IMC

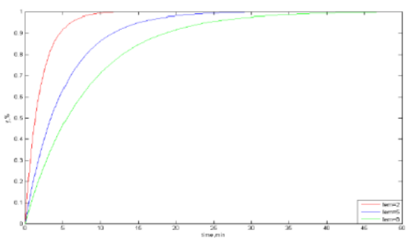

Fig. 6. Simulation of IMC and IMC based PID

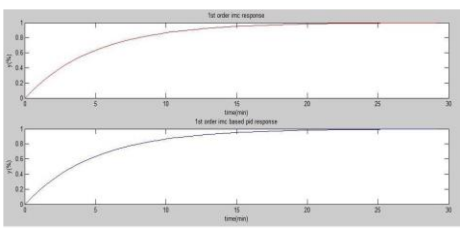

Fig. 7. I Comparison of IMC and IMC based PID

12. IMC based PID for 2nd order system

Now we apply the above IMC based PID design procedure for a second order system with a given process model.

A. Given process model

Gp*(s) = Kp*/[(Tp1*(s)+1).(Tp2*(s)+1)]
Gp*(s)=Gp*(+)(s).Gp*(-)(s)
= 1.Kp*/ [Tp*(s)+1]
Qc*(s) = inv[Gp*(-) (s)]
= [Tp*(s)+1] / Kp*
Qc(s) = Qc*(s). f(s)
= [Tp*(s)+1] / [Kp*.(lem(s) + 1)]
f(s) = 1 / (lem. s + 1)[9]

B. Equivalent feedback controller using transformation

Gc(s) = Qc (s)/(1-Qc(s) Gp*(s))
=[Tp1 .Tp2 s^2 +(Tp1 +Tp2)s+1] / [Kp . lem . s]
(It is the transfer function for the equivalent standard feedback controller)
Gc(s) =[Kc.(Ti .Td.s^2 + Ti.s+1)]/ [Ti. s]
(transfer function for ideal PID controller for second order)[10]

C. PID tuning parameters (on comparison)

Kc = (Tp1 + Tp2) / (Kp. lem)
Ti = Tp1 + Tp2
Td= Tp1.Tp2/ (Tp1 + Tp2)

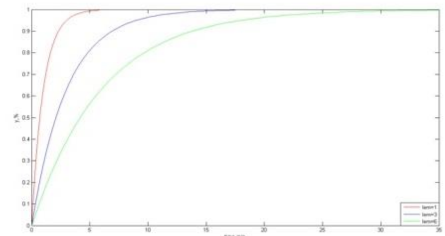

Fig. 8. Simulation IMC based PID for 2nd order system

13. Conclusion

IMC and IMC based PID controllers can be successfully implemented for any industrial process as it is adequately robust towards uncertainty present in the plant parameters. IMC based PID controller algorithm is robust and simple to handle the uncertainty in model and therefore IMC-PID tuning method seems to be a useful trade-off between performance of the closed loop system and we achieve robustness to model inaccuracies with a single tuning parameter. It also provides a good solution to the process with significant time delays which is actually the case with working in real time. IMC has the added advantage of ability to compensate for model uncertainty and disturbances that open loop control does not have.

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