Cascade IMC Controller Design for Heating Furnace Temperature Control

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ABSTRACT
This paper represents the designing and performance evaluation of Modified Ziegler-Nichols Tuning Method and Internal Model Control method for a heat furnace temperature control process. The various results shown in this paper shows how that IMC is a better technique of tuning than conventional tuning methods. Simulation results for the process show the effectiveness of the proposed scheme. From the time domain specifications it has been proved that IMC based system produce less overshoot and reduce the settling time. The entire work has been done in MATLAB/Simulink. The simulation results indicate that IMC method is ideal for dynamic process and comparison between Modified Ziegler-Nichols Tuning method and IMC method shows that IMC tuning algorithm is best suited for setting up values of cascade controller gains, to be used for controlling nonlinear processes such as temperature.

Keywords— Cascaded Control System, Internal Model Control Method, Dynamic performance analysis, Temperature Process control, MATLAB/Simulink.

I. INTRODUCTION
Nowadays Cascade control system is an obvious part of any industries like metallurgy, chemical industries, machinery etc. Because in those industries furnace temperature is the most important parameter and it is a slow dynamic parameter. To control this parameter Cascade control system has been proved more effective than a single loop control system. In this process two controllers are involved. One controller works as primary or inner loop controller and its output is given as a set point of another controller i.e. secondary or outer loop controller. The inner loop behaves like a normal feedback loop and then generates a secondary process variable that serves as the feedback for the primary process. The outer controller control the physical parameter like furnace temperature. So Cascade control system overcome the unacceptable lags and large overshoot which may be introduced in a single loop process.

As this control system became more popular in the industries there are various methods had been introduced to tune the parameter and make the system more stable. As for example, Ziegler-Nichols(ZN) tuning formula, Tyreus-Luyben Tuning formula, Modified Ziegler-Nichols Tuning formula.

As the cascade controller is more complex than single loop controller then it can be assumed that the tuning process should be the same. It is needless to say, that controller tuning is very much process dependent and any improper selection of the controller settings may lead to instability, or deterioration of the performance of the closed loop system. So it is very much important to select a proper tuning method for making the whole process more efficient.

Internal Model Control (IMC) method is one of the effective method for tuning of cascade controller for such dynamic process. The Internal Model Control (IMC) philosophy relies on the Internal Model Principle, which states that control can be achieved only if control system is encapsulates, either implicitly or explicitly, some representation of the process to be controlled. In particular if the control scheme has been developed based on exact model of the process, then control is theoretically possible.

In practice, however process-model mismatch is common, the process model may not invertible and the system is often affected by unknown disturbances. Thus the above open loop control arrangement will not be able to maintain output at set point. Nevertheless, it forms the
basis of the development of a control strategy that has potential to achieve the perfect control. That strategy is known as internal model control (IMC) has general structure.

Additionally to improve robustness, the effect of process model mismatch should be minimized. Since discrepancies between process and model behavior usually occur at the high frequency end of the system’s frequency response, a low pass filter is usually added to attenuate the effect of process model mismatch. Thus, the internal model controller is usually designed as the inverse of the process model in series with low pass filter.

II. METHODOLOGY

A. Internal model control

A.1. the Internal Model principle

The Internal Model Control (IMC) philosophy relies on the Internal Model Principle, which states that control can be achieved only if control system is encapsulates, either implicitly or explicitly, some representation of the process to be controlled. In particular if the control scheme has been developed based on exact model of the process, then control is theoretically possible. Consider for the example the system shown in the diagram below,

Figure 1: Open Loop Control Strategy

A controller $G_c(S)$, is used to control the process, $G_p(S)$ suppose $G_c^p(S)$ is a model of $G_p(S)$ by setting $G_c(S)$ is to be the inverse of the model process,

$$G_c(S) = G_p^p(S)^{-1}$$

And if $G_p(S) = G_p^p(S)$,

$$G_c(S) = G_p^p(S)$$

The eqn. (2) model is exact representation of the process. Then it is clear that the output will always be equal to the set point. Notice that the ideal control performance is achieved without feedback. What this tells us that if we have complete knowledge of the process (as encapsulated in the process model) being controlled, we can achieve perfect control. It also tells us that feedback control is necessary only when knowledge about the process is inaccurate or incomplete.

A.2. The IMC Strategy

In practice, however process-model mismatch is common, the process model may not invertible and the system is often affected by unknown disturbances. Thus the above open loop control arrangement will not be able to maintain output at set point. Nevertheless, it forms the basis of the development of a control strategy that has potential to achieve the perfect control. That strategy is known as internal model control (IMC) has general structure depicted in Figure: 1

![Figure 2: Schematic of the IMC scheme](image)

In the diagram, $d(s)$ is an 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 the signal $d^r(s)$. This is

$$d^r(s) = [G_p(s) - G_p^r(s)]U(s) + d(s)$$

If $d(s)$ is zero for example, then $d^r(s)$ is a measure of difference in behavior between the process and its model. If $G_p(s) = G_p^r(s)$, then $d^r(s)$ is equal to the unknown disturbance.

Thus $d^r(s)$ may be regarded as the information missing in the model, $G_p^r(s)$, and can therefore be used to improve control. This is done by subtracting $d^r(s)$ from the set-point $R(s)$, which is very similar to effecting a set-point trim. The resulting control signal is given by,

$$U(s) = \left\{R(s) - d^r(s)\right\}G_c(s) = \left\{R(s) - [G_p(s) - G_p^r(s)]U(s) - d(s)\right\}G_c(s)$$

Thus, $U(s) = \frac{[R(s)-d(s)]G_c(s)}{1+[G_p(s)-G_p^r(s)]G_c(s)}$ (5)

Since $Y(s) = G_p(s)U(s) + d(s)$

The close loop transfer function of IMC scheme is therefore

$$Y(s) = \frac{[R(s)-d(s)]G_c(s)}{1+[G_p(s)-G_p^r(s)]G_c(s)} + d(s)$$

Or

$$Y(s) = \frac{G_p(s)G_c(s)R(s)+[1-G_c(s)G_p^r(s)]d(s)}{1+[G_p(s)-G_p^r(s)]G_c(s)}$$

(7)

From this close loop expression, we can see that if $G_c(s) = G_p^r(s) - 1$, and if $G_p(s) = G_p^r(s)$, then perfect set-point tracking and disturbance rejection is achieved. Notice that, theoretically even if $G_c(s) = G_p^r(s)$, perfect disturbance rejection can still be realized provide $G_c(s) = G_p^r(s) - 1$.

Additionally to improve robustness, the effect of process model mismatch should be minimized. Since discrepancies between process and model behavior usually occur at the high frequency end of the system’s frequency response, a low pass filter $G_f(s)$ is usually added to attenuate the effect of process model mismatch. Thus, the internal model controller is usually designed as the inverse
of the process model in series with low pass filter, i.e. 
\[ \hat{G}_{IMC}(s) = G_c(s)G_f(s) \]. The order of the filter is usually 
chosen such that \( G_c(s)G_f(s) \) is proper, to prevent the 
excessive differential control action. The resulting close 
loop becomes,

\[
Y(s) = \frac{G_{IMC}(s)G_p(s)R(s)+(1-G_{IMC}(s)G_p(s))d(s)}{1+(G_p(s) - G_p(s))G_{IMC}(s)}
\]  

(8)

### A.3. Practical design of IMC

Designing an internal model controller relatively easy. Given a model of the process \( G_p(s) \), first factor 
\( G_p(s) \) into “invertible” and “non-invertible” components.

\[
G_p(s) = G^-p(s) G^-p(s)
\]  

(9)

The non-invertible component, \( G^-p(s) \), contains the term which is inverted, will lead to instability 
reliability problem, e.g. terms contains positive zeros and 
time-delays. Now, set \( G^-p(s) = G^-p(s) \) and 
then \( G_{IMC}(s) = G_c(s)G_f(s) \), where \( G_f(s) \) is low-pass 
function of appropriate order.

Exe, process model \( G^\sim_p(s) = \frac{2 \exp (-5s)}{1+20s} \), \( G_{IMC}(s) \) 
is designed as follows:

Do the factorization \( G^\sim_p(s) = G^-p(s) G^-p(s) \) where 
\[
G^-p(s) = \frac{2}{1+20s} \text{ and } G^-p(s) = \exp(-5s)
\]  

(10)

Next, set \( G_{IMC}(s) \) to be the inverse of \( G^-p(s) \) in 
series with a low-pass filter

\[
G_f(s) = \frac{1}{(1+\tau_f s)^n}, \text{ where } \tau_f \text{ the filter parameter}
\]  

and n is the order of the filter. This is,

\[
G_{IMC}(s) = \frac{(1+20s)}{2(1+\tau_f s)^n}
\]  

(11)

\( G_{IMC}(s) \) Is proper if n=1, and a good-rule-thumb

is to choose \( \tau_f \) to be twice as fast as the open loop 
response. Hence in this example \( \tau_f=10 \)

Let us look now at the close-loop properties for the system, assuming that \( G_p(s) = G^\sim_p(s) \).

Substituting the relevant information into

\[
Y(s) = \frac{G_{IMC}(s)G_p(s)R(s)+(1-G_{IMC}(s)G_p(s))d(s)}{1+(G_p(s) - G_p(s))G_{IMC}(s)}
\]  

(12)

We get \( Y(s) = G^-p(s)^{-1}G_f(s)G_p(s)R(s) + [1-G^-p(s)^{-1}G_f(s)G_p(s)]d(s) \)

Hence \( Y(s) = G^-p(s)^{-1}G_f(s)G_p(s)R(s) + [1-G^-p(s)^{-1}G_f(s)]d(s) \)

(13)

Thus, we can see that the IMC scheme has the following 
properties, it provides time-delay compensation, the filter 
can be used to shape both the set-point tracking and 
disturbance rejection response at steady-state, and the 
controller will give offset free response.

### B. Cascade control design of heating furnace temperature control

Here in the figure 3, the cascade control system is implemented on a heating furnace where C1 and C2 are 
the primary or master controller and the secondary or slave 
controller respectively. T1 and t2 denotes the temperature 
sensing elements. C.V is the control valve which controls 
the fuel flow in the hearth of the furnace.

![Figure 3: Furnace temperature controller design using cascade control](https://example.com/Figure3.png)

From the theory of cascade control system the 
master controller sends the set point to the slave controller 
and the slave controller sends its control action to the final 
control element of the secondary control section which is 
the fuel control valve. In the furnace the material enters in 
the furnace and the heating element heats the material. 
This heating element works by burning the fuel which enters in 
in the furnace. The temperature of the burning fuel 
or the heating element is sensed by a temperature sensor 
which feed the signal back to the secondary or slave 
controller. At the material output there is another 
temperature sensor which senses the temperature of the 
material which is exhaust from the furnace is feed the 
signal back to the primary or the master controller. 
The main objective of a temperature control of heating furnace 
is the controlling the temperature of the material which 
exasquishing from the furnace. So here in the cascade control 
design the master controller is set to control the 
temperature of the output material and the slave controller 
is set to control the fuel flow. As the fuel flow in the 
furnace determines the intensity of the heating element and 
the heating element heats the material, if the fuel flow will 
be controlled then the temperature of the material can also 
be controlled so that the slave controller controls the fuel 
flow and the master controller sends the set point to the 
slave controller by receiving the feedback signal from the 
material output.
III. PRIOR APPROACH

A. Cascaded PID control system design

Cascade PID (Proportional plus Integral plus Derivative) tuning method for heating furnace temperature control is efficient for this type of non-linear control system but some parameters which draw attention of its disabilities. Following figure 5 [1], is the representation of cascade PID controller for heating furnace and eqn. 14[1] is mathematical representation of PID controller.

\[ P(t) = K_p e_p(t) + K_i \int_0^t e_p(t) \, dt + K_d \frac{de_p(t)}{dt} \]  

Where; \( P(t) \) is control signal applied to the plant, \( K_p \) is proportional gain constant, \( K_i = \frac{K_p}{T_i} \), which is integral constant gain and \( K_d = K_p \times T_d \) is derivative gain constant.

Following figure 4 [1], is furnace cascade PID control system

![Figure 4: Furnace Cascade PID control system model](image)

This system is applied in MATLAB/Simulink as shown in figure 7.

![Figure 5: MATLAB/Simulink model of Cascaded PID controller](image)

IV. OUR APPROACH

A. Cascade IMC system design

The figure 6: shows the furnace of the cascade IMC system. From [1], following equations are transfer functions of Primary and Secondary object respectively.

\[ G_1 = \frac{1}{90} \left(\frac{s+1}{30}\right) \left(\frac{s+1}{3}\right) \]  

\[ G_2 = \frac{1}{10} \left(\frac{s+1}{10}\right)^2 \]  

\[ G_c_1 = \frac{s^2 + 33s + 1}{90s^3 + 2} \]  

\[ G_c_2 = \frac{s^3 + 21s^2 + 6s + 3}{10s^3 + 3s^2 + 3s + 3} \]  

Where equation (17), (18), (19) and (20) are primary process transfer function, secondary process transfer function, primary controller transfer function and secondary controller transfer functions respectively. In this design the primary process model transfer function is similar as primary process transfer function and secondary process model transfer function is similar with secondary process transfer function. So this is an ideal situation for the system design but in the case of batch process or industrial process there would hardly have the ideal situations. So for that the cascade IMC (Model Mismatch) controller is designed figure 8. Here both primary and secondary process model transfer functions are different.
from the primary and secondary process transfer functions respectively.

![Figure 8: MATLAB/Simulink model of cascade IMC (Model Mismatch) Controller design for furnace temperature control](image)

**B. Dynamic performance characteristics**

Dynamic response expresses the change of response of a closed loop system when time is the factor. Following modules are the parameters of this time response.

**B.1. Rise time (tr):** The rise time is the time required for the response to rise from 10% to 90%, 5% to 95%, or 0% to 100% of its final value. For under damped second order systems, the 0% to 100% rise time is normally used. For over damped systems, the 10% to 90% rise time is commonly used. An alternative measure is to represent the rise time as the reciprocal of the slope of the step response at the instant that the response is equal to 50% of its final value.

**B.2. Delay time (td):** The delay time is the time required for the response to reach half the final value the very first time.

**B.3. Settling time (ts):** The settling time is the time required for the response curve to reach and stay within a range about the final value of size specified by absolute percentage of the final value (usually 2% or 5%). The settling time is related to the largest time constant of the control system.

**B.4. Steady-state error (ess):** The steady-state error of a system response is defined as the discrepancy between the output and the reference input when the steady state (t- >∞) is reached.

**B.5. Peak time (tp):** The peak time is the time required for the response to reach the first peak of the overshoot.

**B.6. Maximum (percent) overshoot (Mp):** The maximum overshoot is the maximum peak value of the response curve measured from unity. If the final steady-state value of the response differs from unity, then it is common to use the maximum percent overshoot. It is defined by

\[
\text{Maximum percent overshoot} = \frac{c(t_p) - c(\infty)}{c(\infty)} * 100\%
\]

The maximum overshoot is often used to measure the relative stability of a control system. A system with a large overshoot is usually undesirable.

**B.7. Stability of a system:** A system is stable only when it generates bounded input for bounded output.

An ideal system response will have quick rising and settling time, minimum delay time, zero steady-state error, minimum overshoot and stable.

**C. Simulation results**

After implementing simulations we have obtained following outcomes-

![Figure 9: System response of cascade IMC with disturbances](image)

From figure 9 following performance parameters are obtained

<table>
<thead>
<tr>
<th>Controller Used</th>
<th>Delay Time (Td) in Sec</th>
<th>Rise Time (Tr) in Sec</th>
<th>Settling Time (Ts) in Sec</th>
<th>Peak Overshoot (Mp) in %</th>
<th>Transient Behavior</th>
<th>% Steady State Error (Ess)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Model Control Cascade Controller</td>
<td>0</td>
<td>0</td>
<td>584.7</td>
<td>2.8</td>
<td>Stable</td>
<td>0</td>
</tr>
</tbody>
</table>

So from TABLE I, can be observed that in cascade IMC technique delay time and rise time are ideal and transient behavior is stable. The settling is a bit higher but by the definition of settling time with 2.8% of overshoot it can be called a stable system.
From figure 10 following performance parameters are obtained

**TABLE II**

<table>
<thead>
<tr>
<th>Controller Used</th>
<th>Time Domain Performance Parameters</th>
<th>% Steady State Error (E∞)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMC Model Mismatch Cascade Controller</td>
<td>Delay Time (Td) in Sec 0</td>
<td>Rise Time (Tr) in Sec 0</td>
</tr>
</tbody>
</table>

Now from TABLE II, it can be observed with stable transient behavior and ideal rise time and delay time the system response is even better as its settling time is low and with 2.5% of overshoot it can be called stable condition from the definition of settling time.

**D. Comparison between the responses of cascade IMC and cascaded PID controlling technique**

In the previous section, the response curve of time v/s material temperature of the heating furnace system designed in cascade control implemented by the IMC method is shown. Here in this section, the comparison between cascade IMC and PID controlling technique is discussed. This PID controller is tuned by the Ziegler-Nichols tuning method.

The details are shown below:

**TABLE III**

<table>
<thead>
<tr>
<th>Controller Used</th>
<th>Time Domain Performance Parameters</th>
<th>% Steady State Error (E∞)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ziegler-Nichols PID Controller</td>
<td>Delay Time (Td) in Sec 2.763</td>
<td>Rise Time (Tr) in Sec 2.456</td>
</tr>
<tr>
<td>Modified Ziegler-Nichols PID Controller</td>
<td>5.296</td>
<td>7.644</td>
</tr>
<tr>
<td>Internal Model Control Cascade Controller</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IMC Model Mismatch Cascade Controller</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
V. CONCLUSION

From the Ref. [1] it has observed the values of temperature process controller of heating furnace by using cascade PID tuning methods. After that cascade IMC system for heating furnace has implemented to tune the temperature and obtain parameters. The outcome of all is compared and tabulated as Table. From the table it can be observed-

- Ziegler-Nichols PID controller shows that the response is stabilizing fast compared to Modified Ziegler-Nichols PID controller, but with peak overshoot of 58.20% may damage the system severely.
- Modified Ziegler-Nichols PID controller shows that the response has lower settling time than Internal Model Control cascade controller, but its delay time, rise time and pick overshoot is higher than the Internal Model Control cascade controller, which is a drawback for the Modified Ziegler-Nichols PID controller system.
- In the IMC Model Mismatch cascade controller, the value of delay time, rise time and peak overshoot are better in compare to other controllers. Furthermore, it provides major benefit in terms of stable transient behavior and minor overshoot.

Therefore, it is concluded that the IMC Model Mismatch is most efficient cascade control technique to be used for controlling non-linear system such as temperature for heating furnace.

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