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Linear Control Theory Based Approach towards the Conversion Technique from a Higher order plus dead time (HOPDT) model into a Lower order plus dead time (LOPDT) model using Compensator

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ABSTRACT
In control system application used in industries, the plant has generally been modeled as a second-order or first order system with time delay and the controller is either of the P, PI or the PID type. But in practical situation, initially the order of the plant is found to be higher order rather first or second order which shows uncontrollable oscillation in the system even the controller may not work properly. The main objective of this paper shows some process of conversion technique from a Higher order plus dead time model (HOPDT model) into a Lower order plus dead time model (LOPDT model) using linear control theory. Due to the huge popularities of tuning method in the process industries, lots of methods have been developed to find out the parameters of the PID controller such as a Z-N method, IAE, ITAE and IMC method. Here in this work, designing the control system has been done using proposed tuning process in two steps. The first one is called tracking and the second one is said to be disturbance rejection by reducing the system order to make a robust design. Finally some higher order systems are taken and then converted into lower order system using the proposed conversion technique which gives the desired simulation result.
***KEYWORDS**: Order of a system, Compensator ,PID Tuning.*

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I. INTRODUCTION

Because of the prolonged use of a system (performance), the parameters of the system can change. So to improve the transient response and the steady state response of a plant, a controller (in the domain) is being introduced along with the plant in a cascading arrangement[1][2]. But in practical modeling of any plant must be represented by HOPDT model (Higher order plus dead time model) [3][4]which makes it towards the nonlinearity. PID controllers are the most important and popular controller used infield of research. The rule to tune the PID Controller had proposed by Ziegler and Nichols in the year of 1942.Tuning of PID controllers for HOPDT is not simple as this model is unable to generate peaks for monotonic (all poles lie on the negative real axis) processes. In this work, poles of higher order system are allocated in such a way that model poles are cancelled out by controller zero though proper cancellation is never possible. As a result, the higher order system is reduced into a second order system and then tuning of the PID controller has been applied [16]. In many applications might require two some specific control action to get the appropriate system and that can be found by setting the other parameters to zero. If accuracy is required for a plant, then the PI controller is sufficient to achieve the requirements [7][8]. When the speed of the system is a priority, then the PD controller is suitable and then an integral parameter is set to zero. So PID controller is used as per requirement of different processes. PID controller takes input as a difference between set point and feedback signal. Tuning of PID controller by using the root locus method is for any dynamics; whether it is the high order or low order, high dead time or low dead time, the oscillatory or monotonic system.

II. APPLIED METHOD FOR HIGHER ORDER REDUCTION

The transfer function of a plant is represented here by G(s). Consider a transfer function is given by

$$G(s) = \frac{e^{-st_0}}{as^2+bs+c} \quad (1)$$

Depending on the values of a, b, and c, the model can be characterized into real or complex poles. Hence it is easy to represent both non-oscillatory as well as oscillatory processes [15][14]. Again a PID controller can be written in the form of $K(s) = K_P + \frac{K_I}{s} + sK_D$. Putting s=jω into equation 1, and then divide into real and imaginary parts, we need four equations for finding out four unknowns. So by fitting the process gain G(s) at two nonzero frequency points it can be constructed into the equation of K(S). Now two different points are chosen like $s = j\omega_c$ and $s = j\omega_b$, where angle of $j\omega_c$ is -180 degree and angle of $j\omega_b$ is -90 degree. After calculating real and imaginary parts, the following equations are formed and given below.

$$c - a\omega_c^2 = \frac{\cos(\omega_c L)}{-IG(j\omega_c)I} \quad (2)$$

$$b\omega_c = \frac{\sin(\omega_c L)}{IG(j\omega_c)I} \quad (3)$$

$$c - a\omega_b^2 = \frac{\sin(\omega_b L)}{IG(j\omega_b)I} \quad (4)$$

$$b\omega_b = \frac{\sin(\omega_b L)}{IG(j\omega_b)I} \quad (5)$$

After solving these above equations the values of a, b and c are calculated and given below.

$$a = \frac{1}{\omega_c{}^2 - \omega_b{}^2}\left[\frac{\sin(\omega_b t_0)}{IG(j\omega_b)I} + \frac{\cos(\omega_c t_0)}{IG(j\omega_c)I}\right] \quad (6)$$

$$b = \frac{\sin(\omega_c t_0)}{\omega_c IG(j\omega_b)I} \quad (7)$$

$$c = \frac{1}{\omega_c{}^2 - \omega_b{}^2}\left[\omega_c{}^2 \frac{\sin(\omega_b t_0)}{IG(j\omega_b)I} + \omega_b{}^2 \frac{\cos(\omega_c t_0)}{IG(j\omega_c)I}\right] \quad (8)$$

Here an assumption is made to get t_0 is given below.

$$\frac{\sin(\omega_c t_0)}{\cos(\omega_b t_0)} - \frac{\omega_c}{\omega_b}\frac{IG(j\omega_c)I}{IG(j\omega_b)I} = \Omega \quad (9)$$

For tuning of the controller, the range at which system is stable is found out by using Routh-Hurwitz criterion, making 1+G(s)H(s) = 0 and $k < \frac{b}{\tau_0}$. The range of k gives the stability. The speed of response of a process is inversely proportional to its equivalent time constant[8]. Equivalent time constant has been calculated and given below.

$$\frac{1}{\tau} = \frac{c}{\sqrt{b^2 - 4ac}}, b^2 - 4ac < 0 \quad (10)$$

$$\frac{1}{\tau} = \frac{b}{2a}, b^2 - 4ac > 0 \quad (11)$$

Rewriting the form of PID controller design equation as follows

$$K(s) = k.\frac{\alpha s^2 + \beta s + \gamma}{s} \quad (12)$$

where $\alpha = \frac{K_D}{K}, \beta = \frac{K_P}{K}, \gamma = \frac{K_I}{K}$.

Now to cancel out the proposed models pole, a controller is chosen whose α=a,β=b,γ=c. So the open loop transfer function can be represented as given below.

$$G(s).H(s) = K\frac{e^{-st_0}}{s} \quad (13)$$

III. EFFECT OF CONTROLLER PARAMETERS

The initial work of a PID controller is to read a Set point and then calculate the required output by calculating PID responses. The controller input is basically the error between the expected output and the final output. The position of a controller in a closed loop system is given below in Figure 1.

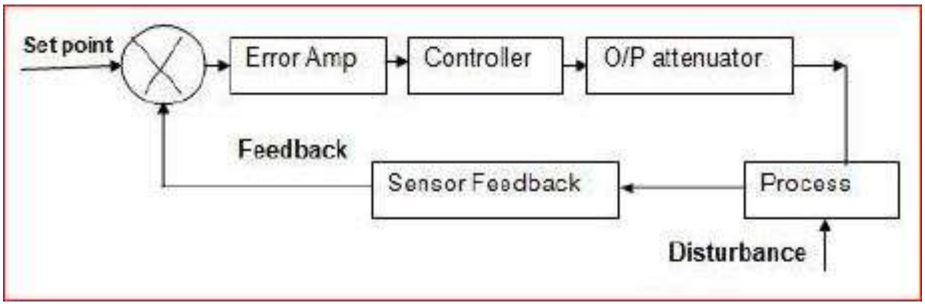

Figure 1: Position of a controller in a closed loop system

This difference is changed by the actuator part of the controller to produce a signal to the plant, according to the following relationship given below [5] [6].

$$K_p\left(1 + T_d s + \frac{1}{T_i s}\right) \quad (14)$$

Where K_p , T_d , T_i are the controller's parameters. The effect of each controller parameter K_p , T_d , T_i on a closed loop system is summarized in the table 1 given below.

Closed loop Response	**Rise Time**	**Overshoot**	**Settling Time**	**Steady State Error**
K_p	Decreases	Increases	Small change	Decreases
T_i	Decreases	Increases	Increases	Zero
T_d	Small change	Decreases	Decreases	Not affected

Table 1: The effect of each controller parametersK_p , T_d , T_i.

It is widely been used in programmable logic controllers, SCADA, remote terminal unit, etc.[10][9] Due to high requirement of best tuning procedures which tune the plant in such a way that optimized solution can be provided, many tuning methods have already been developed in which some methods give better response for speed of the system and some show good response for stability. FOPDT/ SOPDT model is very popular because it is very easy to tune but for certain applications FOPDT model does not fulfill the requirements, as cardiac muscle cannot completely be represented a simple second order system, rather higher order system. So it is required to design the system in such a way that attains the requirement of the real life applications, both of the aspects, good stability and high speed of the response[13]. In this research work HOPDT (Higher order plus dead time model) model is proposed in which higher order system is reduced in a second order system.

IV. PROCESS MODELING FOR HIGHER ORDER SYSTEM

Here in this dissertation, some modeled transfer functions are considered as a plant transfer function with respect to control system terminology. The input and output of a plant to be controlled is given below in figure 2.

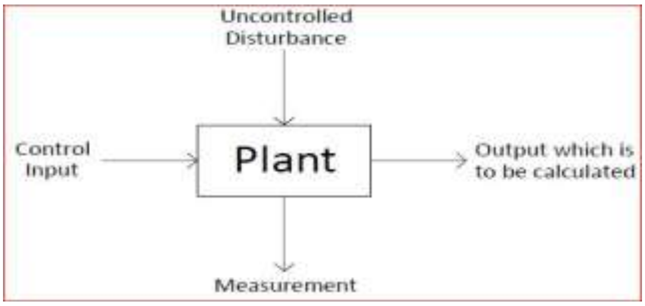

Figure 2: The input and output of a plant.

The main objective of designing the control system so as to meet some criteria in such a way that the output can be set to a fixed value which is called as reference value, due to some unknown disturbances reference value should be maintained. The first one is said to be tracking, the second one is said to be disturbance rejection, if both the condition is met then the control system design can be a robust design [11][12]. In figure 3 the use of controller is shown with a help of block diagram.

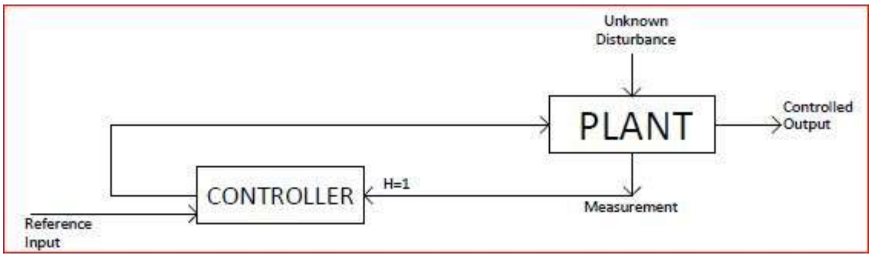

Figure 3: Control system with controller.

Here initially, HCS is considered as a simple FOPDT (First-order plus dead time) model where the transfer function is represented as G(s) and given by the following equation.

$$G(s) = \frac{Ke^{-s.L}}{Ts+1} \qquad (15)$$

where L represents delay time of the proposed model, T gives the Time constant and K represents the gain.
Taking first-order and second-order derivatives with respect to s,

$\frac{G'(s)}{G(s)} = -\frac{T}{1+Ts} - L$(16)

$\frac{G''(s)}{G(s)} - \left(\frac{G'(s)}{G(s)}\right)^2 = \frac{T^2}{(1+Ts)^2}$(17)

Putting s is zero and considering TA as an average time,

$T_A = -\frac{G'(0)}{G(0)} = T + L$(18)

G(0) gives the DC gain of the system and this can be calculated from the previous equations.

V. EXPERIMENTAL RESULTS WITH SIMULATION

Here some higher order oscillatory system has been taken for experimental purpose. Say for example, a servo motor system with its transfer function is given below.

$G(s) = \frac{1}{s^4+10s^3+37s^2+60s+36} e^{-.4s}$(19)

Two points are $\omega_b = 0.7886$ and $\omega_c = 1.7780$. Frequency response at this points are $G(j\omega_b)$= 0.02249 and $G(j\omega_c)$ =0.01148.Using these values the lower order transfer function is given as follows.

$G(s) = \frac{1}{19s^2+47s+39} e^{-.75s}$(20)

The PID parameters have been calculated and controller transfer function is given below.

$K(s) = 32.2 + \frac{24.4}{s} + 12.6s$(21)

Another example of DC series motor used in industry whose transfer function is taken and given below.

$G(s) = \frac{1}{s^4+9s^3+29s^2+39s+18} e^{-.1s}$(22)

Two points are $\omega_b = 0.8$ and $\omega_c = 1.9$. Frequency response at this points are $G(j\omega_b)$= 0.04 and $G(j\omega_c)$ =0.01. Using these values the lower order transfer function is given as follows.

$G(s) = \frac{1}{18s^2+31s+20} e^{-.45s}$(23)

The PID parameters have been calculated and controller transfer function is given below.

$K(s) = 32 + \frac{19.4}{s} + 17.6s$(24)

The simulation result of equation (20) considering controller transfer function from (21) is given below in figure 4.

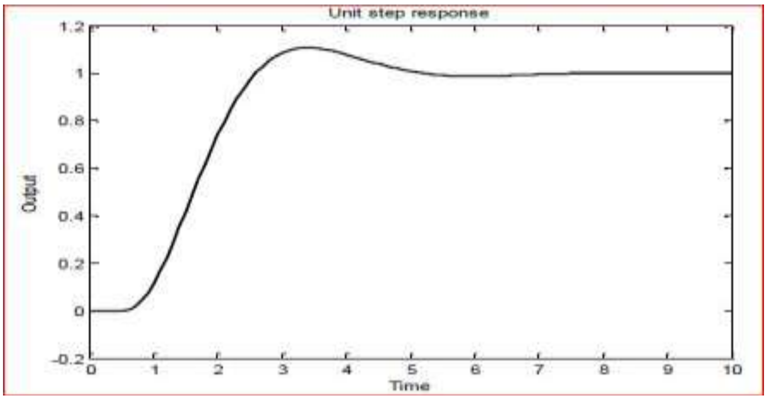

Figure4. Step response of Servo motor.

Response values of the step input have been tabulated in Table 2 as follows.

Parameter	Response value
Peak Time	3.12 sec
Rise Time	2.32 sec
Peak Value	1.13
Settling Time	5 sec
Overshoot Percentage	13%

Table 2: The Response values of the step input for Servo motor.

The simulation result of equation (23) considering controller transfer function from (24) is given below in figure 5.

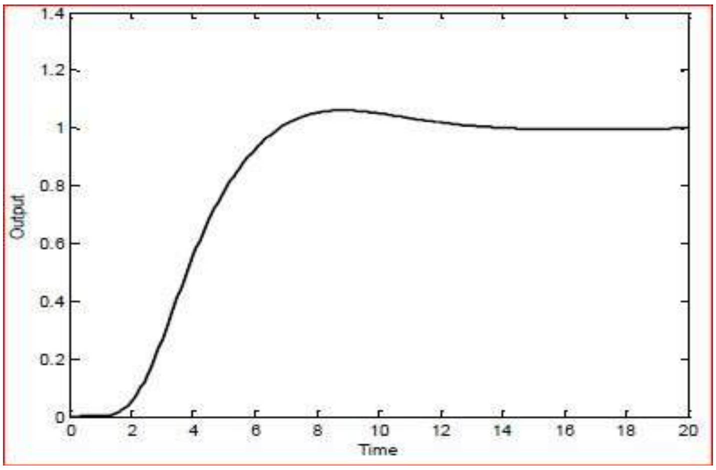

Figure 4: Step response of DC series motor.

Response values of the step input have been tabulated in Table 3 as follows.

Parameter	Response value
Peak Time	8 sec
Rise Time	6.12 sec
Peak Value	1.1
Settling Time	10 sec
Overshoot Percentage	9%

Table 3: The Response values of the step input for DC series motor.

The experimental result shows the stability of the converted system means LOPDT model.

VI. CONCLUSION

The main objective of this paper shows some process of conversion technique from a Higher order plus dead time model (HOPDT model) into a Lower order plus dead time model (LOPDT model) using linear control theory. Due to the huge popularities of tuning method in the process industries, lots of methods have been developed to find out the parameters of the PID controller such as a Z-N method, IAE, ITAE and IMC method. Here in this work, designing the control system has been done using proposed tuning process in two steps. The first one is called tracking and the second one is said to be disturbance rejection by reducing the system order to make a robust design. Finally some often used higher order systems are taken and then converted into lower order system using the proposed conversion technique which gives better simulation result. This conversion process also shows the good stability which will be beneficial for future research work.

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