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# DESIGN OF FEED FORWARD COMPENSATOR FOR A THERMAL PROCESS

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**Abstract:** In this paper design of feedforward compensator for thermal process is proposed. The merits and demerits of feedforward and feedback control schemes are discussed. Feedforward compensators such as static, static with delay, Lead-Lag, and Lead-Lag designed and their performances are discussed in detailed using Matlab simulation. The effectiveness of feedforward controller also analysed with First order plus dead time (FOPDT) thermal process. Further nonlinearfeedforward controller also designed to improve disturbance rejection ability.

Keywords: Feed forward, FOPDT, PID controller,Compensator

## I. Introduction

The PID controller treatment to both Steady state response and transient, most efficient solution to many real time process. The PID control schemes provide the advance in digital technology and science of automatic control in a wide spectrum. Feed forward controller is a system with a feed forward behavior which responds to the control signal in a predefined manner without taking into account the reaction of the load. Feed forward controller behaves contrary to feedback controller which adjusts the output by considering the reaction of the load. The feed forward control can be utilized for various applications such as drum level control. The design of feed forward compensator is very simple. An ideal feed forward compensator may have endless high frequency gain because of derivative exploit and its more difficult structure. Without any disturbance from the feedback controller the gain will be chosen the load is eliminated in steady state value [1].Different examples exists to illustrate the impact of disturbance on the controlled variable [2]. The disturbance that enters the control loop in the process is called as load disturbance. The main objective of this paper is to simultaneously improve local control performance and manage closed-loop coupling between pools by distributed control [3].The proportional term to providing the overall control action proportional to the error signal through all gain factor [4].

## II. PROPOSED DESIGN OF FEEDFORWARD- FEEDBACK CONTROL

### *A. Basic relationships*

**A** schematic diagram of feed forward – feedback control system is shown in Fig.1.
The Figure.1 consists of the basic feedback loop with feedback controller C, process $P_1$ $P_2$, and the signals setpoint$y_{sp}$ , control signal u and process output y. A measurable load disturbance d is influences the feedback loop according to the diagram, with transfer function $P_2$ $P_3$ between load d and process output y.
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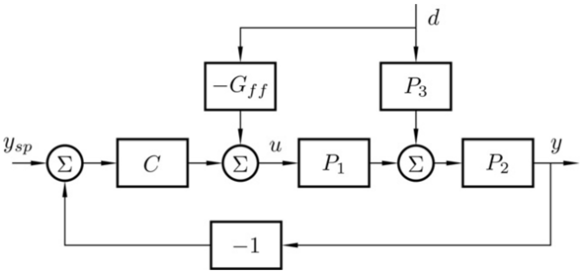


Fig.1: Block diagram of feedforward –feedback control

The disturbance effect on the output variable when the feed forward controller is implemented by the first order system with time delay alone may be written as

$$P_1 = \frac{K_1}{1+ST_1} e^{-SL_1} \quad ,P_2 = \frac{K_2}{1+ST_2} e^{-SL_2}$$

$$P_3 = \frac{K_3}{1+ST_3} e^{-SL_3} \qquad (1)$$

The transfer function of the PID controller is

$$C = K\left(1 + \frac{1}{ST_i} + ST_a\right) \qquad (2)$$

The response of feedback control system
Example 1:

For the simulation analysis, the process transfer functions are considered by assuming
$K_1 = K_2 = 1$, $K_3 = 2$, $L_1 = L_2 = 1$, $L_3 = 2$

The AMIGO tuning rules are:

PI CONTROLLER:

$$K_C = \frac{0.15}{K_p} + \left(0.35 - \frac{L\,T}{(L+T)^2}\right)\frac{T}{K_p L} \qquad (3)$$

$$T_i = 0.35L + \frac{13LT^2}{T^2 + 12LT + 7L^2}$$

PID CONTROLLER:

$$K_C = \left(0.2 + 0.45\frac{T}{L}\right) \qquad (4)$$

$$T_i = \left(\frac{0.4L + 0.8T}{L + 0.1T}\right)L$$

$$T_d = \frac{0.5LT}{0.3L + T}$$

The feedback controller parameters for Ziegler Nichols and AMIGO are shown in Table1

Table1 PID Controller parameters

| Controller | | ZN | AMIGO |
|---|---|---|---|
| P | $K_p$ | 0.96 | |
| PI | $K_p$ | 0.872 | 0.25 |
| | $K_I$ | 6.66 | 2.0 |
| PID | $K_p$ | 1.12 | 0.65 |
| | $K_I$ | 4.0 | 1.09 |
| | $K_D$ | 1.0 | 0.384 |

The servo and regulatory response of feedback controller is shown in figure 2 and 3.From servo and regulatory response, PID controller produced good response compared to other controllers. (i.e. P and PI controllers). The performance evaluation the based on ISE and IAE are analyzed and shown in Table 2 and Table 3.The working PID controller is analysed using ISE and IAE. The table shows PID controller produced good results compared to other controllers.

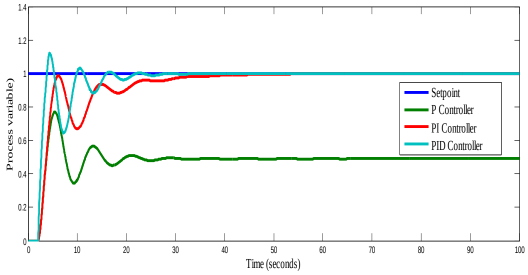


Figure2 Servo Response of feedback control system.

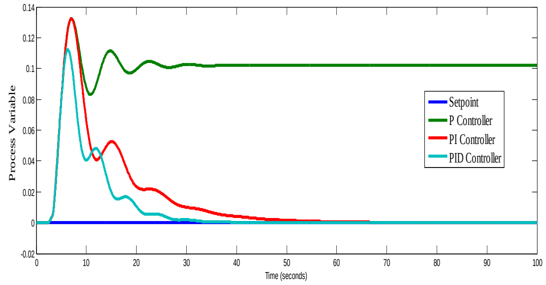


Figure 2 Regulatory response of feedback control system.

Table.2 Error performance analysis of feedback control system (Servo Response)

| Controller | ISE | IAE |
|---|---|---|
| P | 2706 | 52.02 |
| PI | 6.66 | 44.44 |
| PID | 3.96 | 15.99 |

Table 3 Error performance analysis of feedback control system (Regulatory Response)

| Disturbance | Controller | ISE | IAE |
|---|---|---|---|
| d=10% | P | 23.96 | 4.89 |
| | PI | 0.66 | 0.44 |
| | PID | 0.39 | 0.15 |
| d=20% | P | 95.88 | 9.7 |
| | PI | 1.33 | 1.77 |
| | PID | 0.79 | 0.63 |

The comparison of servo and regulatory response of ZN and AMIGO tuning methods are shown in Figure 4(a) and 4(b).

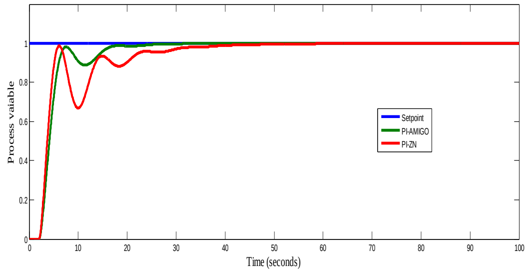


Figure 4 Comparison of Servo response of feedback control system.

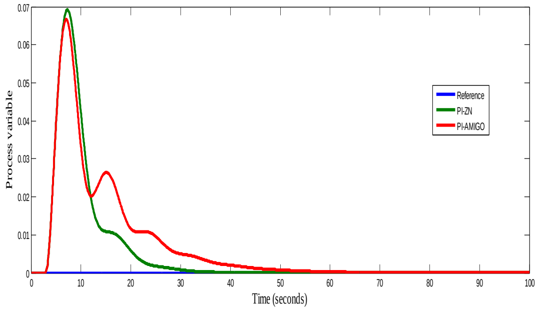


Figure 4(b) Comparison of regulatory response of feedback control system

## III. PERFORMANCE EVALUATION OF FEEDFORWARD CONTROL SYSTEM

Proportional+ Integral+ Derivative (PID) controllers are mostly used in many industrial applications. The performance of the controller is heavily depends on the tuning parameters and less knowledge of the process alone sufficient to design them. The effective design of a controller is much easier nowadays due to the increase in computational capabilities. Feedback control does not provide predictive control action to recompense for the effects of known or assessableturbulence. The limitation of a PI controller is analyzed based on ISE, IAE on a conical tank level process. An auto tuning process controller with improved load disturbance rejection is presented. Traditional PID controllers cannot anticipate the disturbance inputs or the time evolution of the storage system.

### A. *Servo and regulatory response of feedforward control*

Feedforward control is a controlling technique. The limitations of feedforward control are analyzed using simulation results.

Four structures of the feedforward compensator Gffare treated in this paper:

Static : $G_{ff} = K_{ff}$ (5)

Static with delay : $G_{ff} = K_{ff} e^{-SL_{ff}}$

Lead- Lag : $G_{ff} = K_{ff} \frac{1+sT_Z}{1+sT_P}$

Lead-lag with delay : $G_{ff} K_{ff} \frac{1+sT_Z}{1+sT_P} e^{-SL_{ff}}$

More compound structures are seldom used in process control plants. In fact, the stable feedforward compensator is the most common structure, and feedforward by just a gain in the compensator can often make severe improvements in the control performance compared to pure feedback control.

### B. *Open-loop design*

The open loop feedforward controller is intended by neglecting the feedback controller and also the effect of feedback on the troublenegative response. It means that the open-loop transfer function stuck between d and y is measured, which is given by

$$Y = P_2(P_3 - P_1 G_{ff})D \quad (6)$$

Perfect feedforward, which means that the effect of d is eliminated in y, is obtained when

$$G_{ff} = \frac{P_3}{P_1} = \frac{K_3}{K_1} . \frac{1+s\,T_1}{1+s\,T_3} e^{-s(L_3 - L_1)} \quad (7)$$

which means that

$$K_{ff} = \frac{K_3}{K_1}, T_z = T_1, \ T_P = T_3 \ ,$$
$$L_{ff} = L_3 - L_1 \quad (8)$$

when $L_3 < L_1$, the optimal parameters given by (8), the feedforward compensator becomes negative. This means that ideal feedforward is not probable in this casing and feedforward compensator assumed to be $L_{ff} = 0$.

In this case a static feedforward controller

$$G_{ff} = K_{ff} = \frac{K_3}{K_1} \quad (9)$$

The feedforward compensator eliminates the effect of the disturbance in steady state.

A summary of the open-loop design rules designed for the different compensator Structures is:

Static : $G_{ff} = \frac{K_3}{K_1}$ (10)

Static with delay: $G_{ff} = \frac{K_3}{K_1} e^{-s(L_3 - L_1)}$

Lead –Lag : $G_{ff} = \frac{K_3}{K_1} \frac{1+sT_1}{1+sT_3}$

Lead-Lag with delay :

$$G_{ff} = \frac{K_3}{K_1} \frac{1+sT_1}{1+sT_3} e^{-s(L_3 - L_1)}$$

### C. *Design of feedforward compensator for $L_3 \geq L_1$*

The process transfer functions are

$$P_1 = \frac{1}{1+s} e^{-s}, \quad (11)$$

$$P_2 = \frac{1}{1+s} e^{-s},$$
$$P_3 = \frac{1}{1+2s} e^{-2s}$$

The feedback controller is PI controller tuned with AMIGO rule. The four different feedforward compensators are

Static : $G_{ff} = 1$ (12)

Static with delay: $G_{ff} = e^{-s}$

Lead –Lag : $G_{ff} = \frac{1+s}{1+2s}$

Lead-Lag with delay :

$$G_{ff} = \frac{1+s}{1+2s} e^{-s}$$

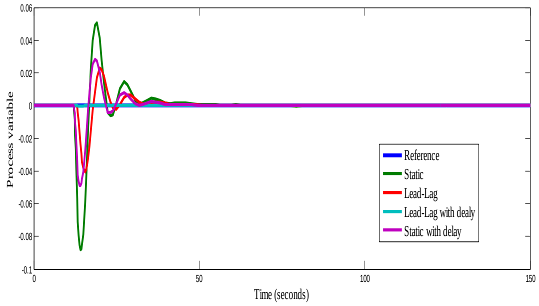


Figure 5.Response of feedforward compensator when $L_3 \geq L_1$

Figure 5 shows the load disturbance responses of four different feedforward designs. The perfect feedforward is obtained when the lead-lag compensator with delay is used. When only static feedforward compensator is used large deviation in from the setpoint.

### D. *Design of feedforward compensator for $L_3 < L_1$*

The process transfer functions are

$$P_1 = \frac{1}{1+2s} e^{-2s}, \quad (13)$$

$$P_2 = \frac{1}{1+s} e^{-s},$$

$$P_3 = \frac{1}{1+s} e^{-s}$$

The PI controller is tuned with AMIGO rule. The four different feedforward compensators are

Static : $G_{ff} = 1$ (14)

Static with delay :$G_{ff} = e^{s}$

Lead –Lag :$G_{ff} = \frac{1+2s}{1+s}$

Lead-Lag with delay :

$$G_{ff} = \frac{1+2s}{1+s} e^{s}$$

From Equation (14) the feedforward compensators static with delay and Lead-Lag with delay are physically unrealizable. In this case only static and Lead-Lag feedforward compensators are considered for the analysis. Figure 6 shows the response of feedforward controller when $L_3 < L_1$. The static and Lead-Lag compensators are not perfect compensators. Because of that there is deviation in the process output.

## IV. DESIGN OF FEEDFORWARD COMPENSATOR FOR THERMAL PROCESS

The performance of the feedback control depends mainly on the selection of suitable controller parameters, and the open loop transfer function of the process. For many processes, it is very difficult to develop the fundamental mathematical process models to tune a specific control loop. However, it is possible to develop a transfer function based model by conducting a plant test. The well-known plant test is to give a step change in the manipulated input, and observe the measured process output. In this way, the best model has been developed, to provide an equal match between the model output and the practical plant output. The behaviour of the process is represented by a FOPDT model as

$$G_{PRC}(s) = \frac{K}{\tau s + 1} e^{-Ls} \quad (15)$$

The process parameters are the static gain (K), the time constant (□), and the dead time (L) of the plant derived from the transient response experiment using the step tuning method.

Consider, the FOPDT open loop transfer function of the process is

$$G_p(s) = \frac{1.1}{34s + 1} e^{-12s} \quad (16)$$

The disturbance process transfer function is

$$G_d(s) = \frac{15}{20s + 1} e^{-20s} \quad (17)$$

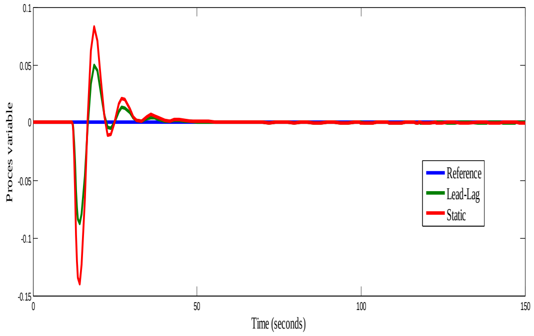


Figure 6 Response of feedforward compensator when $L_3 < L_1$

### A. *Servo and Regulatory Responses of Feedforward-Feedback Controller*

The limitations of feedforward control are analyzed using the simulation results. Using Equations (16) and (17) the transfer function of the feedforward controller is formulated as given in Equation (18).

$$G_f(s) = \frac{1.36(34s + 1)}{(20s + 1)} e^{-8s} \quad (18)$$

The servo and regulatory responses of the feedforward – feedback control scheme is shown in Figure 7

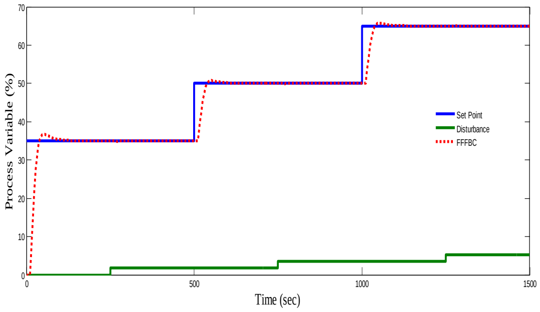
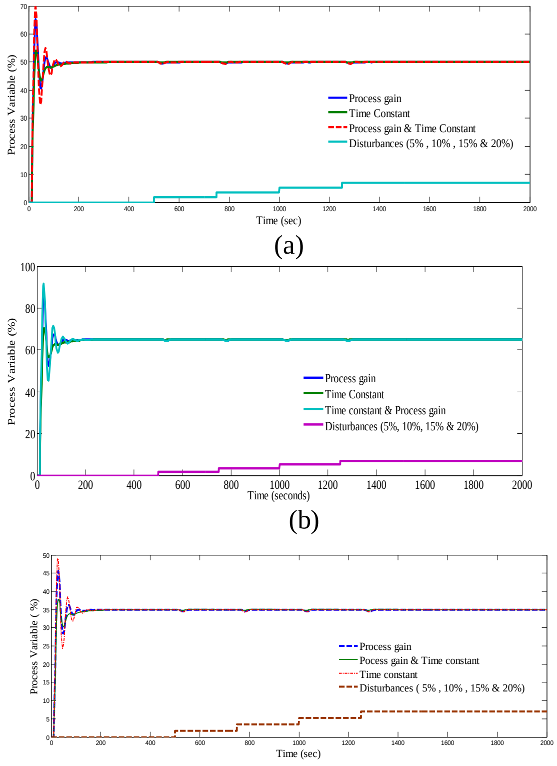


**Figure 7 Servo and regulatory responses of the FF-FBC**

The performance of the FF-FBC is analysed for different disturbance magnitudes (5%, 10%, 15% and 20%), for various modelling errors, such as process gain, time constant and combined process gain and time constant. The process gain is considered as 1.5 instead of 1.1. The servo and regulatory response, of the process with modelling errors is shown in Figure 8 (a - c) and its performance analysis is shown in Table 4. The deviation in the process variable due to modelling error, is very less compared to only the feedback control system. The designed FF-FBC is effective in eliminating the effects of the modelling errors. It is clear that the FFC is sensitive to modelling errors and the effects of modelling errors are eliminated by augmenting the FBC.



(a)

(b)

(c)

Figure 8 Servo and Regulatoryresponses of the FF-FBC with modelling errors at (a) 35% operating point, (b) 50% operating point and (c) 65% operating point

Table 4 Performance analysis of the FF-FBC with modeling errors

| Error factors | Disturbance | Servo and regulatory response of FF-FBC with modeling errors at various operating points | | | | | |
|---|---|---|---|---|---|---|---|
| | | 35% | | 50% | | 65% | |
| | | ISE | IAE | ISE | IAE | ISE | IAE |
| K=1.5 & τ =30 | d=5% | 330408.1 | 574.81 | 663503.3 | 814.55 | 1111817.6 | 1054.42 |
| | d=10% | 348183.1 | 590.07 | 688548.3 | 829.78 | 1144229.3 | 1069.68 |
| | d=15% | 366418.8 | 605.32 | 714103.0 | 845.04 | 1177101.8 | 1084.94 |
| | d=20% | 385100.0 | 620.56 | 740438.6 | 860.48 | 1210695.4 | 1100.31 |
| τ =30 | d=5% | 582206.2 | 763.02 | 1188174.4 | 1090.0 | 2008020.9 | 1417.04 |
| | d=10% | 582203.9 | 763.02 | 1188174.1 | 1090.0 | 2008017.1 | 1417.04 |
| | d=15% | 582201.9 | 763.02 | 1188173.6 | 1090.0 | 2008342.5 | 1427.16 |
| | d=20% | 582294.0 | 763.02 | 1188160.5 | 1090.0 | 2007837.0 | 1416.98 |
| K=1.5 | d=5% | 330408.0 | 574.81 | 663604.9 | 814.60 | 1111858.9 | 1054.44 |
| | d=10% | 348183.0 | 590.07 | 688698.2 | 829.87 | 1144008.3 | 1069.58 |
| | d=15% | 366423.9 | 605.32 | 714254.6 | 845.13 | 1176884.0 | 1084.84 |

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## V. CONCLUSION

In this work, feedback and feedforward controller are designed and implemented. The merits and demerits of each controller scheme are discussed. An improved disturbance rejection is obtained using static, static with delay, Lead-Lag, Lead-Lag with delay feedforward compensators. Model uncertainties and disturbance effects are addressed, using the nonlinear feedforward controller. It improves the process output with the best rise time and less settling time, without design modifications.

In practice, most of the real time industrial stand data are linked with extent noise. The collection of sufficient, suitablegood qualityquality data is still a real problem.

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