



Derivative Proportional – Integral Controller Using Nelder-Mead Optimization for Glycerine Purification Heating Process

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Abstract: It is important to purify the crude glycerine before to convert them into value-added products. Such dark colored crude has high free fatty acid content that can be removed via heating process. This paper focuses mainly on the heating control system, which has contributed to the improvement of the glycerine purification process system. The design of Derivative Proportional – Integral controller for the glycerine temperature control loop system could demonstrate some improvement of the glycerine heating process control response in term of process settling time and percent overshoot. Derivative Proportional – Integral is a proposed controller where Proportional and Derivative control actions operate on process variables rather than error signals. Meanwhile, the integral mode is connected to the forward path where the error signal is used as an input to the control mode. The output of the two control modes is then subtracted to drive the process. The Derivative Proportional – Integral controller was designed using the Nelder-Mead optimization algorithm with objective function of the Integral Time Absolute Error criteria calculated using Simpson's one-third rule. The control performance of the proposed controller was analyzed by comparing the rise time, percent overshoot and settling time of the response with that of the conventional PID controller. The simulation results show that the Nelder-Mead optimization algorithm can be used and can produce a good control system with zero percent overshoot and shorter heating time compared to the achievements of the PID control system. In addition, the robustness test of the controller has shown that the proposed control system can effectively detect changes in the operating temperature. The control performance shown by the proposed controller is excellent. The Derivative Proportional – Integral control system designed based on optimization algorithm techniques can improve the performance of the glycerine purification process heating system to meet the purified glycerine requirements.

Keywords: Derivative Proportional – Integral, Optimization, Glycerine, Heating Process

1. Introduction

Glycerin purification is an essential process for Pharmaceutical and Cosmetic industries as these industries consume only pure glycerine as a raw ingredient in their end-product manufacture. According to [1] and [2], pure

glycerine is referred to the glycerine that has undergone the process of removing the contaminants presence in the crude. Such dark colored crude has a high free fatty acid (FFA) content which can be removed via heating process. The process is significantly depending on the operating temperature [3-5]. A proper temperature control system is necessary to produce purified glycerine with accepted oxidative stability and increase the efficiency of the purification process system. This paper proposed a Derivative Proportional-Integral (DPI) controller using Nelder-Mead optimization algorithm for glycerine purification heating process system. The details of the implementation are described in the following sections of the paper.

2. Literature Review

In oil refining industry, the purification process is carried out at a temperature sufficiently high for the crude glycerine or fat to be liquid. However, higher temperatures can worsen the level of oxidative stability [6-9]. Owing to the heat requirements, an optimum temperature is recommended to achieve the desired result [9]. Studies by previous researcher [10] have shown that an optimum operating temperature will increase the process capability by reducing the viscosity of the oil. Previous studies [9-11] have also shown that unlimited increase in temperature beyond optimum and excessive prolonged heating has resulted in the production of non-triglyceride components which contribute to excessive secondary oxidation. A number of publications on the process of FFA removal method are available in the literature [10-13]. Nevertheless, the papers focus more on chemical-based techniques. To date, the techniques related to the process control method for crude glycerine purification heating process have not been scientifically discussed. Hence, the latest findings from any of the published papers related to the temperature control system applications that can be adapted to the process are reviewed.

2.1 PID Controller

It is reported in [14-16] that most of process control applications in industry still use the conventional Proportional-Integral-Derivative (PID) controller to regulate temperature and many other industrial process variables. The key drawbacks of PID control, however, are the undesirable control action that contribute to significant high percent overshoot and longer settling time [17]. In order to reduce these undesirable control effects, the PID control structure has been modified by many researchers, resulting in the Integral-Derivative-Proportional (IDP) [17] and Integral-Proportional-Derivative (IPD) [18, 26-28] control structures, which are used in particular applications.

In recent year, the Proportional Integral- Proportional Derivative (PI-PD) [19-21] control structure has been used in unstable system with time delay. The control structure was modified in which the PI action is on the error and the PD action is on the process variable. However, the difficulty of the controller is where the controller parameters appear in a much more complicated and the tuning process become tedious. It is also reported that the PI-PD control structure is not suitable for a process that exhibit large time delay and uncertainties [29].

Investigation done by [22] showed that the selection of a suitable modified PID structure depends on the desired specifications required by the designer or on the nature operation of the process. It is reported in [22] that the control action does not depend on the kind of the process while the process behaviour depends on the control structure. If the process requires a fast control action and can tolerate some spike in the control signals, then the parallel PID with filter and PI&D structure can be selected. Meanwhile, if the process cannot tolerate any undesirable effects and can accept slow response due to limitation of the actuator, then I&PD control structure can be selected.

2.2 Controller Tuning Technique

The challenge in the design of the controller is to set its control parameters. The appropriate performance of a particular process control system is highly dependent on the correct values of the control parameters. Various tuning methods for controllers are available in the literature. In recent years, the methods of optimization algorithms have drawn researcher interest. In [26], IPD controller parameters that are optimized using particle swam intelligence gave better performance compared to Ziegler Nichols for a First Order Lag Integrating plus Time Delayed (FOLIPD) process model. Various optimization methods used for IPD controller parameter adjustment such as bacterial foraging optimization search algorithm [28], meta-heuristic optimization techniques known as Adaptive Tabu Search (ATS) [18] and Cuckoo Search [27] can be found in the literature. In their work, the optimal controller parameters were determined by minimising the multiple objective performance criterion using search algorithm. Another popular optimization algorithm that has been receiving a lot of attention are Particle Swam Optimization (PSO) [26], Genetic Algorithm (GA) [30] and Nelder-Mead Simplex Algorithm [29].

Even though controller tuning methods are widely available in the literature, good control performance is application specific in which the correct choice of design method mainly depends on the process control objectives and process dynamic response [25]. For instance, though one process may be best operated with fast and aggressive control action, another may be better applicable for a slow and gentle response.

3. Proposed Controller for Glycerin Purification Heating Process

In this work, Derivative Proportional-Integral (DPI) control structure shown in Fig. 1 is proposed for glycerine temperature control loop. It is proposed to improve the limitations of the PID control structure [23, 24]. The effectiveness of this proposed control structures for glycerine purification process is then comparatively analyzed with the conventional PID control structures in terms of transient response performance criterion.

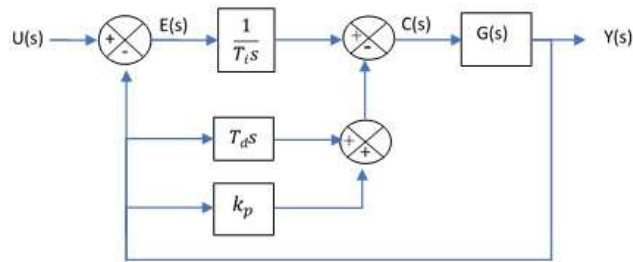


Fig. 1 – DPI control structure

The DPI controller is a modified form of a parallel PID control structure. The modification mostly involves the repositioning of the derivative and proportional control actions in the control loop. As shown, the integral term responds on error signal whereas the other two terms work on the process output. The output signal from the controller can be written as in (1).

$$U(s) = \frac{1}{T_i s} E(s) - (K_p + T_d s) Y(s) \tag{1}$$

3.1 Controller Parameters Adjustment

The main objective of the proposed controller is to make the percent overshoot and settling time for glycerine purification heating process as small as possible. In this paper, the optimal values for controller gains were determined by an optimization algorithm that minimizes the objective function of the system.

The Integral Time Absolute Error (ITAE) criterion calculated using Simpson’s one-third rule formula was proposed as an objective function of the system. Then, the objective function guides the optimization algorithm to search the optimum controller parameters based on the initial controller parameters setting and process model. This is as illustrated in Fig. 2. The searching for the controller parameters was achieved using Nelder-Mead Simplex Direct method [29] that repeatedly generates a sequence of interest points covering the optimum point of objective function based on the initial parameters setting. The initial parameters were set to be those determined by Ziegler-Nichols reaction-curve method [23, 25] shown in (2), (3) and (4) where K , T , L are process gain, process time constant and process time delay respectively.

$$K_p = \frac{1.2KT}{L} \tag{2}$$

$$T_i = 2L \tag{3}$$

$$T_d = 0.5L \tag{4}$$

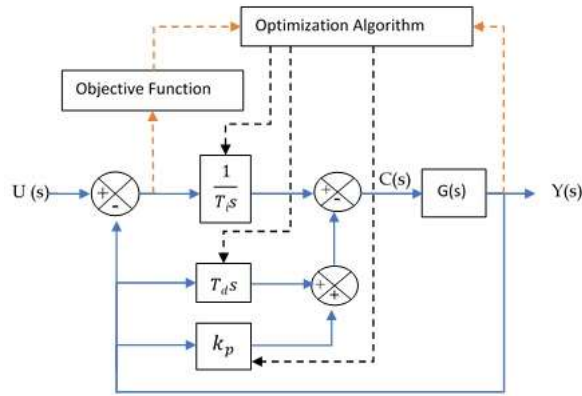


Fig. 2 – Tuning method for DPI controller

At each repetition, the objective function values are arranged as shown in (5) where X_1 is the best optimum point and X_{n+1} is the worse optimum point. The other four possible points was calculated based on reflection, expansion, contraction and shrink operations. In this paper, the algorithm uses the midpoint of the line to calculate the respective points.

$$f(x_1) \leq f(x_2) \leq f(x_3) \leq \dots \leq f(x_{n+1}) \tag{5}$$

The algorithm steps are as follows:

- Let X_{n+1} is the worse point. Compute the reflection point, X_r using (6).

$$x_r = \frac{1}{n} \sum_{i=1}^n x_i + \alpha \left(\frac{1}{n} \sum_{i=1}^n x_i - x_{n+1} \right) \tag{6}$$

- Evaluate the objective function. If $f_1 \leq f_r < f_n$ replace X_{n+1} with X_r
- If $f_r < f_1$, compute the expansion point, X_e using (7)

$$x_e = \frac{1}{n} \sum_{i=1}^n x_i + \beta \left(x_r - \frac{1}{n} \sum_{i=1}^n x_i \right) \tag{7}$$

- Evaluate the objective function. If $f_e < f_r$, replace X_{n+1} with X_e otherwise with X_r .
- If $f_n \leq f_r < f_{n+1}$, compute the outside contraction, X_{oc} using (8)

$$x_{oc} = \frac{1}{n} \sum_{i=1}^n x_i + \gamma \left(x_r - \frac{1}{n} \sum_{i=1}^n x_i \right) \tag{8}$$

- Evaluate the objective function. If $f_{oc} < f_r$, replace X_{n+1} with X_{oc} otherwise, shrink
- If $f_r > f_{n+1}$, compute the inside contraction point, X_{ic} using (9).

$$x_{ic} = \frac{1}{n} \sum_{i=1}^n x_i - \gamma \left(x_r - \frac{1}{n} \sum_{i=1}^n x_i \right) \tag{9}$$

- Then, shrink for $2 \leq i \leq n+1$ using (10) and proceed to the next iteration.

$$x_i = x_1 + \delta(x_i - x_1) \tag{10}$$

3.2 Glycerine Heating Process Model

In this paper, the glycerine purification heating process was modelled as the First Order plus Delay Time (FOPDT) shown in (11) in which the process parameters of K , T and L are determined using two-point method on the experimented open loop step response. In this method, the time taken for the response to reach 28.3% and 63.2% of

total output change is used to estimate the time delay and time constant of the process [25]. The delay time is then approximated using Pade approximation as shown in (12).

$$G_p = \frac{Ke^{-sL}}{1 + sT} \tag{11}$$

$$e^{-t_d s} = \frac{-0.5t_d s + 1}{0.5t_d s + 1} \tag{12}$$

3.3 Controller Performance Evaluation

The glycerine purification heating process performance was measured using the important closed loop system specifications such as overshoot and settling time. The settling time is the time for the process variable to reach and remain within 5% of its final output value. A value for maximum overshoot ratio that appears to be widely accepted in the literature [42] is around 10% and for decay ratio a widely accepted value is 0.25. The robustness of the controller was evaluated based on the set point change tracking where the output is expected to follow the changes with minimum steady state error.

4. Results and Discussion

The glycerine purification heating process model is estimated as shown in (13). It can be seen that the process is categorized as lag dominant type because the ratio of the time delay to time constant for the process is relatively equal to 0.12. This indicate that the process tend to have the problems like overshoot in which the controller with high gains is needed in the control loop.

$$G_p = \frac{4.8(1 - 210s)}{(1 + 3397s)(1 + 210s)} \tag{13}$$

The closed loop step response of PID Ziegler-Nichols controller is shown in Fig. 3a. It is observed that the rise time was quite fast, but the response is detected with a significant overshoot and some undershoot for glycerine purification heating process. Basically, the high overshoot can cause the settling time becomes slower to track the set point. The transient response performance of both controllers that designed using Ziegler-Nichols method are presented in Table 1.

Table 1 – Transient response performance

| Ziegler-Nichols Method | Rise Time (sec) | Settling Time (sec) | Overshoot (%) |
|----------------------------|-----------------|---------------------|---------------|
| PID 1 st Tuning | 298.5 | 7701.2 | 60.4 |
| PID Refined Tuning | 561.8 | 7521.1 | 27.5 |
| DPI Controller | 1599 | 8486.5 | 7.3 |

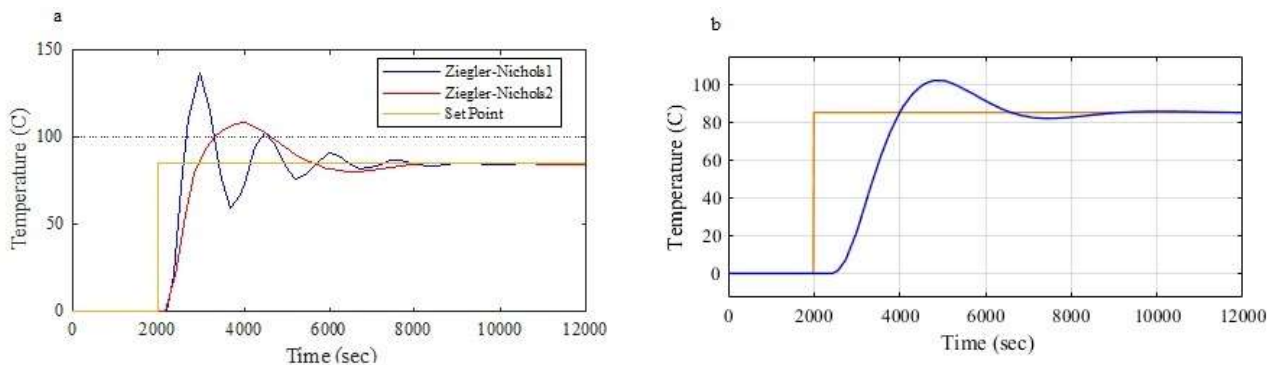


Fig. 3 - (a) PID Ziegler-Nichols performance comparison; (b) DPI using Ziegler-Nichols method

The PID Ziegler-Nichols controller showed fast rising time but penalize with high overshoot which is 60.4% deviate from the set point. The overall settling time of the response is achieved at 7701.2 second. As shown, the rise time and the settling time of the controller are slightly increase. It can be seen that the overshoot of the closed loop PID Ziegler-Nichols controller is decrease to 27.5% and the response was settled at 7521.1 seconds after refined tune. The step response of the designed DPI controller using Ziegler-Nichols techniques is as shown in Fig. 3b. The transient response performance is tabulated in Table 1. As shown, the response of DPI controller gave an acceptable result in term of overshoot even though not much improvement can be seen for rise time and settling time as compared to the PID controller. The response of the controllers designed using suggested method is as shown in Fig.4a. The transient response performance of the controllers is tabulated in Table 2. It can be seen that the controlled system with DPI controller provides better output response than the conventional PID. As shown, the PID controller produces much greater percent overshoot even though the rise time is smaller than those from DPI controller. The controlled system with the DPI controller gives faster response with 0% overshoot and satisfactory practical control signal. The control signal for PID and DPI controllers is depicted in Fig. 4b. As shown, the PID controller has very high 'kick' control signals and takes longer time forwards a smooth transition signal to the ac power controller as compared to the DPI controller. It can be seen that DPI control signal shows modest overshoot, settles quickly and display no offset.

Table 2 – Transient response performance

| Nelder-Mead Optimization Method | Controller | Rise Time (sec) | Settling Time (sec) | Overshoot (%) |
|---------------------------------|------------|-----------------|---------------------|---------------|
| $K_p = 1.61$ | PID | 315.65 | 5062.7 | 45.3 |
| $T_i = 633.11$ | DPI | 1598.4 | 3958.1 | 0 |
| $T_d = 179.33$ | | | | |

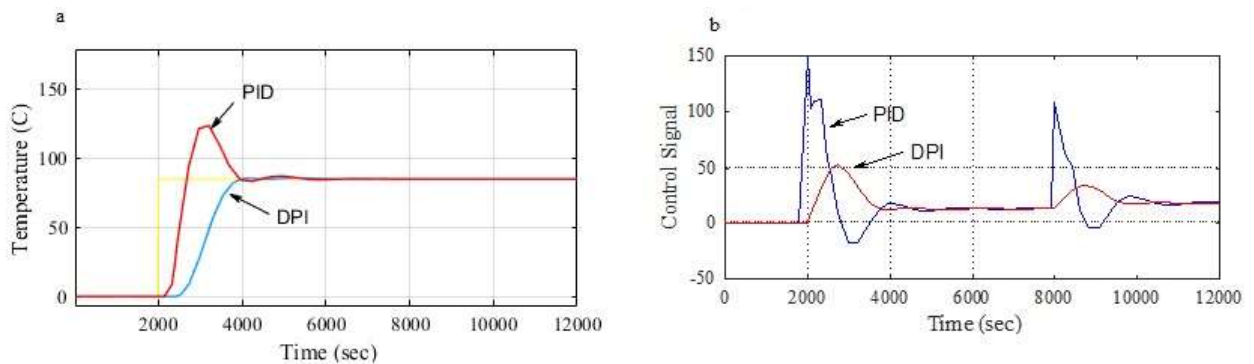


Fig. 4 – (a) Controller performance comparison; (b) Control signal in comparison

The response of the DPI controller to track the input temperature change is shown in Fig. 5. From the plot, it was observed that the DPI controller managed to track the set point changes very well.

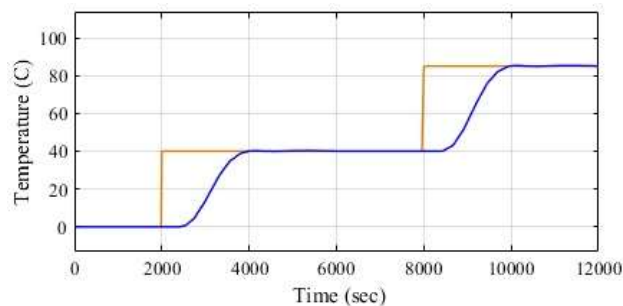


Fig. 5 – Set point change DPI response

The results showed that the DPI response has a satisfactory performance which exhibit a slowly smooth response with acceptable control action. By comparing with the conventional PID controller, the implementation of the proposed control structure DPI gave better control performance with 0% overshoot, acceptable settling time and smooth control signal. The DPI controller was found to be effective in trailing the input temperature changes and thus can be applied in the glycerine purification process system.

5. Conclusion

The DPI controller with the integral term act on the error signal and add to the other two controller terms which act on the process variable is successfully designed and tested. It is shown that the control structure of the proposed controller which is designed using ITAE criterion objective function and Nelder-Mead Simplex Direct optimization algorithm is workable and able to provide good control performance. The experimental results were encouraging and the controlled dynamic response of the process with the DPI controller were judged satisfactory in terms of transient control performance i.e. settling time and percent overshoot. In general, the controller was able to handle set point changes very well.

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