



Soft Computing Techniques Based Design of Feedback PID Controller for an Industrial Process

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Abstract: Proportional Integral derivative (PID) controllers are widely used in industrial process control. With its three term functionality providing regulation to both transient and steady state responses, PID control offers the simplest and most efficient solution to many industrial control problems. Tuning of PID gain parameters continuous to be important as these parameters has great influence on the stability and the performance of the control system. Many techniques are used to tune PID controller. In this paper, Soft Computing technique Genetic Algorithms are proposed as a method for tuning of PID controller. The performance of Genetic Algorithms based PID controller is compared with feedback PID controller tuned by trial and error method, feedback plus feedforward controller, Zeigler-Nicholas PID controller. Shell and tube heat exchanger process is used for performance analysis of different controllers. Simulation results show that the gains obtained using Genetic Algorithms provide better performance than those obtained by Ziegler-Nicholas method and other controllers.

Keywords: Proportional Integral Derivative (PID) Controller, Tuning, Ziegler-Nicholas (ZN) Method, Genetic Algorithms, Shell and Tube Heat Exchanger.

I. INTRODUCTION

Process is defined as the operation in which the solid or liquid materials converted into more useful state. Process is the physical system we are attempting to control or measure (e.g. steam boiler, heat exchanger, distillation column etc.). The performance of process is influenced by process variable (PV) which is the specific physical quantity we are measuring in the process (e.g. temperature, pressure, level, flow etc.). The value, at which we desire the process variable to be maintained at, is called Set Point (SP).

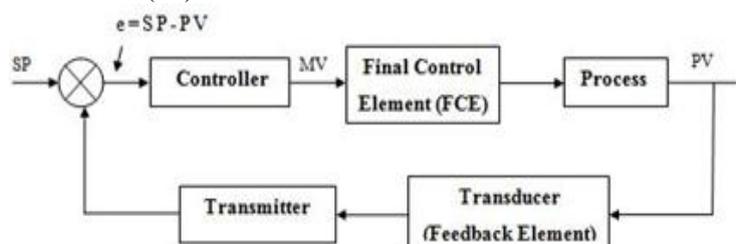


Figure 1 Basic Block diagram of Process Control

A device that directly senses the process variable and converts the sensed physical quantity into electrical quantity, is called Transducer. A device that converts the signal produced by transducer into a standardized instrumentation signal such as 3-15 psi air pressure, 4-20 mA DC electric current etc., which may then be conveyed to an indicating device, controlling device, or both, is called Transmitter. A device that receives the PV signal from transmitter, compares that signal to SP for that process variable, and calculates an appropriate output signal to be sent to FCE (e.g. control valve). The output signal generated by controller is called Manipulating Variable (MV).

A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable. The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. The three term functionality of PID controller provides treatment to both transient and steady state responses. Since the invention of PID controller in 1910 largely owing to Elmer Sperry's ship auto pilot and the Ziegler-Nicholas tuning methods in 1942, the popularity of PID controller has grown tremendously. The PID controller calculation involves three separate parameter proportional, integral and derivative gains. The proportional value determines the reaction of current errors, the integral value determines the reaction based on the sum of recent errors, and derivative value determines the reaction based on the rate at which the error has been changing and the weighted sum of these three terms is used to regulate the process via the

final control element. PID controller is mostly tuned by Zeigler-Nicholas method. The Soft Computing technique based tuning method for a PID controller considerably reduces the overshoot and settling time.

Transfer function of PID controller is given by

$$C(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s \right) = K_p + K_i \frac{1}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s}$$

Where, K_p = Proportional gain, K_i = Integral gain, K_d = Derivative gain, T_i = Integral time constant and T_d = Derivative time Constant.

II. HEAT EXCHANGER SYSTEM

Heat exchanger is commonly used in chemical processes to transfer heat from a hot fluid through a solid wall to a cooler fluid. It transfers heat between two fluids without mixing them up. Shell-and-tube heat exchangers are probably the most common type of heat exchangers applicable for a wide range of operating temperatures and pressures. Shell-and-tube heat exchangers find widespread use in refrigeration, power generation, heating and air conditioning, chemical processes, manufacturing, and medical applications. The main purpose of a heat exchanger system is to transfer heat from a hot fluid to a cooler fluid, so temperature control of outlet fluid is of prime importance. To control the temperature of outlet fluid of the shell and tube heat exchanger system a conventional PID (Proportional Integral Derivative) controller can be used.

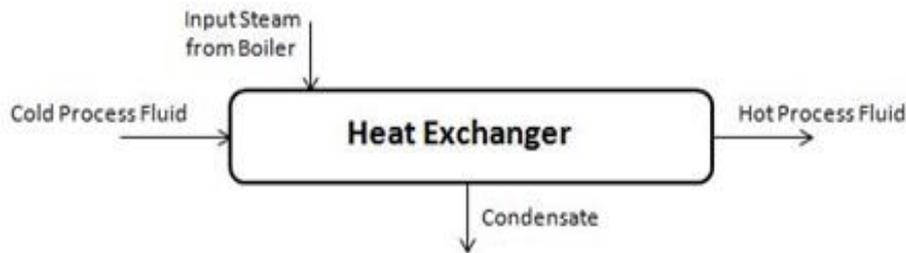


Figure 2 Basic Principal of Heat Exchanger

A typical interacting chemical process for heating consists of a chemical reactor and a shell and tube heat exchanger system. The process fluid which is the output of the chemical reactor is stored in the storage tank. The storage tank supplies the fluid to the shell and tube heat exchanger system using a pump and a non returning valve. The heat exchanger heats up the fluid to a desired set point using super heated steam at 180°C supplied from the boiler. The super heated steam comes from the boiler and flows through the tubes, whereas, the process fluid flows through the shells of the shell and tube heat exchanger system. The first assumption is that the inflow and the outflow rate of fluid are same, so that the fluid level is maintained constant in the heat exchanger. The second assumption is the heat storage capacity of the insulating wall is negligible. A thermocouple is used as the sensing element, which is implemented in the feedback path of the control architecture. The temperature of the outgoing fluid is measured by the thermocouple and the output of the thermocouple (voltage) is sent to the transmitter unit, which eventually converts the thermocouple output to a standardized signal in the range of 4-20 mA. This output of the transmitter unit is given to the controller unit. The controller implements the control algorithm, compares the output with the set point and then gives necessary command to the final control element via the actuator unit. The actuator unit is a current to pressure converter and the final control unit is a control valve. The actuator unit takes the controller output in the range of 4-20 mA and converts it in to a standardized pressure signal, 3-15 psig. The valve actuates according to the controller decisions. Figure1 shows the basic feedback control scheme implemented in a shell and tube heat exchanger system. There can be two types of disturbances in this process, one is the flow variation of input fluid and the second is the temperature variation of input fluid.

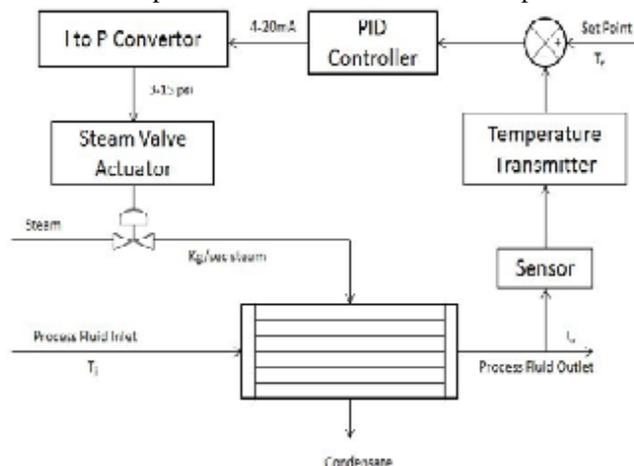


Figure 3 Control Loop for Heat Exchanger

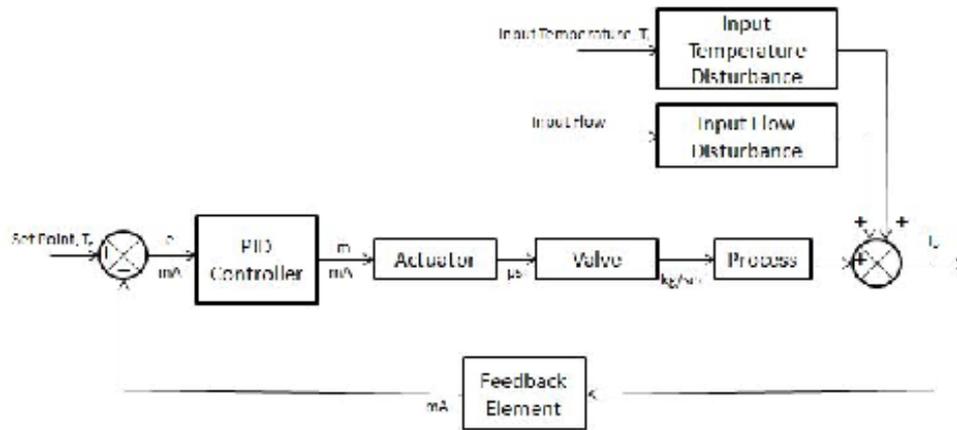


Figure 4 Block Diagram of Control Loop for Heat Exchanger

III. MATHEMATICAL MODEL OF HEAT EXCHANGER

General form of first order process model is represented as

$$G(s) = \frac{K_p}{\tau s + 1} \quad (\text{First order})$$

$$G(s) = \frac{K_p}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (\text{Second Order})$$

Where K_p process gain and τ is time constant

The heat exchanger response to the steam flow has a gain of $50^\circ \text{C}/(\text{kg}/\text{sec.})$ and time constant of 30 sec. The heat exchanger response to the fluid flow has gain of $3^\circ \text{C}/(\text{kg}/\text{sec.})$ and to the inlet temperature is 1.

$$\text{Transfer function of Heat exchanger} = \frac{50}{30s + 1}$$

$$\text{Flow disturbance} = \frac{1}{30s + 1}, \quad \text{Temperature Disturbance} = \frac{3}{30s + 1}$$

The control valve has maximum capacity of 1.6 kg/sec of the steam, linear characteristics and a time constant of 3 sec.

The nominal pressure of the valve is 3-15 psi

$$\text{Control Valve Gain} = \frac{1.6}{15 - 3} = \frac{1.6}{12} = 0.13$$

$$\text{Transfer function of control valve} = \frac{0.13}{3s + 1}$$

$$\text{Current to pressure converter has a constant gain} = \frac{15 - 3}{20 - 4} = \frac{12}{16} = 0.75$$

$$\text{Including the constant gain of the current to pressure in control valve transfer function, transfer function of control valve} = \frac{0.1}{3s + 1}$$

Sensor is calibrated in the range of 50°C to 150°C and time constant is of 10 sec.

$$\text{Sensor Gain} = \frac{16\text{mA}}{(150 - 50)^\circ \text{C}} = 0.16\text{mA}/^\circ \text{C}$$

$$\text{Transfer function of Sensor} = \frac{0.16}{10s + 1}$$

Overall Transfer function of process is represented as

$$G(s) = \left(\frac{0.13}{3s + 1} \right) \left(\frac{50}{30s + 1} \right) = \frac{5}{90s^2 + 33s + 1}$$

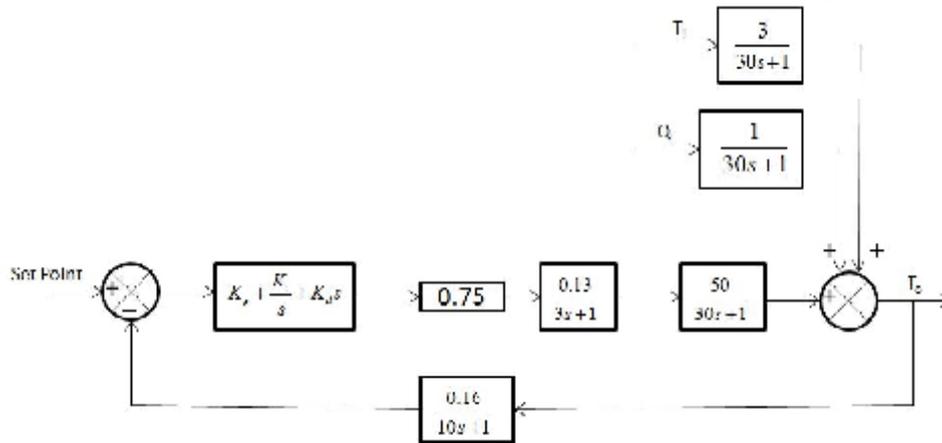


Figure 5 Transfer Function Model for Heat Exchanger Control Loop

IV. IMPLEMENTATION OF PID CONTROLLER

The process of computing and setting the optimal values of K_p , K_i and K_d to get desired response from a control system, called tuning. Tuning of PID controller is a wide area of research with many tuning rules. The three parameters of PID controller are mostly tuned by Ziegler-Nichols but this method is not always suitable for every kind of process dynamics. The process has also its own dynamics such as some process have long dead time, some process has oscillatory behaviour and some other process can be unstable. So there are different set of tuning rules for each and every process dynamics. Many model based controller techniques such as internal model based control, dynamic matrix control are used in conjunction with PID controller to improve the dynamic response of the process. Apart from the conventional techniques of controller tuning there are many soft computing based intelligent tuning methods that imitate human intelligence with the goal of creating tools provided with some human-like capabilities (such as learning, reasoning, and decision making), and are based on fuzzy logic, neural networks, and probabilistic reasoning techniques such as genetic algorithms, swarm optimization etc.

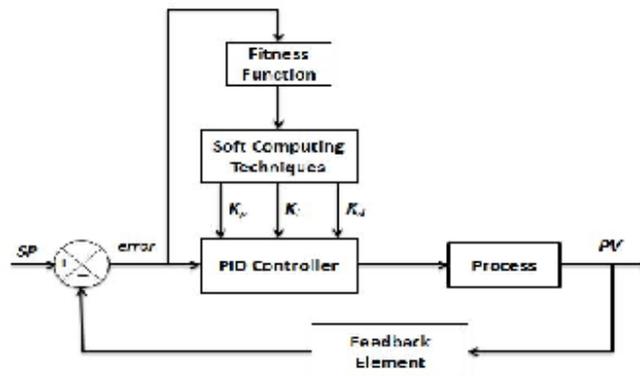


Figure 6 Block diagram of Soft Computing Techniques Based PID Controller

A. Ziegler-Nicholas (ZN) Method

Ziegler Nicholas method is a popular method for tuning P, PI, PID controllers. This method starts by zeroing the integral and differential gains and raising the proportional gain until the system is unstable. The value of K_p at the point of instability is called K_{max} ; the frequency of oscillation is f_o . The method then backs off the proportional gain a predetermined amount and sets the integral and differential gains as a function of f_o .

Table 1 Parameters of Z-N PID Controller

Controller	K_p	K_i	K_d
Z-N PID	25.73	5.86	27.82

B. Genetic Algorithms for PID Controller Tuning

Genetic Algorithms are search optimization techniques based on the mechanisms of Darwin's principle of natural selection. The searching process is similar to that in nature where a biological process in which stronger individual is likely to be the winner in a competing environment. GAs starts with an initial population containing a number of chromosomes where each one represents a solution of the problem which performance is evaluated by a fitness function. Basically, GAs consists of three basic operations: selection, crossover and mutation. Selection gives more reproductive chances to the fittest individuals. During crossover some reproduced individuals cross and exchange their genetic characteristics. Mutations may occur in a small percentage and cause a random change in the genetic material, thus contributing to introduce variety in the population. The evolution process guides the GAs through more promising

regions in the search space. The application of these three basic operations allows the creation of new individuals which may be better than their parents. This algorithm is repeated for many generations and finally stops when reaching individuals that represent the optimum solution to the problem.

The implement of the tuning procedure through GAs starts with the definition of the chromosome representation. The chromosome is formed by three values that correspond to the three gains to be tuned in order to achieve a satisfactory behaviour. The gains K_p , K_i and K_d are binary strings numbers and characterize the individual to be evaluated.

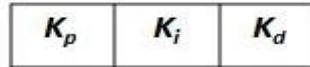


Figure 7 Chromosome Definition

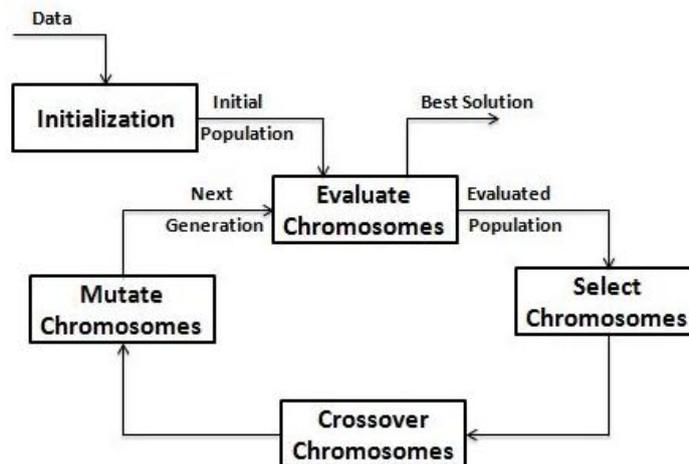


Figure 8 Optimization Using Genetic Algorithms

Table 2 Parameters of Genetic Algorithms

Parameter	Value
Population Size	100
Bit Length of Chromosome	10
Number of Generations	100
Crossover Probability	0.8
Mutation Probability	0.05
Selection Method	Rank Method
Crossover Type	Single Point Crossover
Mutation Type	Uniform Mutation

The optimal values of the conventional PID controller parameters K_p , K_i and K_d , are found using Genetic Algorithms. All possible sets of controller parameter values are chromosomes whose values are adjusted so as to minimize the objective function, which in this case is the error criterion.

$$IAE = \int_0^{\infty} |e(t)| dt \quad ISE = \int_0^{\infty} e^2 dt \quad ITAE = \int_0^{\infty} t |e(t)| dt \quad ITSE = \int_0^{\infty} t^2 e(t) dt$$

Table 3 Parameters of GA-PID Controller

Controller	K_p	K_i	K_d
GA-PID	24.87	0.069	483.85

IV. RESULTS

To control the outlet process fluid temperature of shell and tube heat exchanger different controller are used. Performance of different controller based on step response and error indices is summarized below.

Table 4 Results for Transient Response of Different Controllers

Controller	Overshoot %	Settling Time (sec)
Feedback PID	29.56	115.2
Feedback plus Feedforward	25.1	91.3
ZN-PID	16	5.29
GA-PID	0	0.175

Table 5 Performance Indices of Different Controllers

Controller	IAE	ISE	ITAE	ITSE
Feedback PID	5.55	0.3	610.8	11.75
Feedback plus Feedforward	4.14	0.25	340.1	5.107
ZN-PID	2.36	0.12	190.4	2.84
GA-PID	1.48	0.07	90.3	1.36

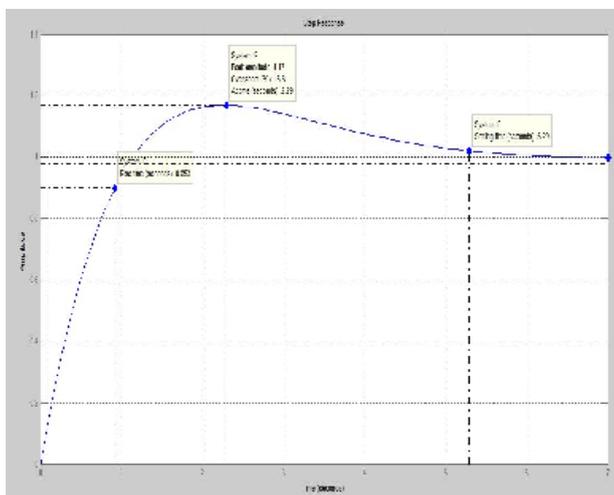


Figure 9 Step Response of ZN-PID Controller

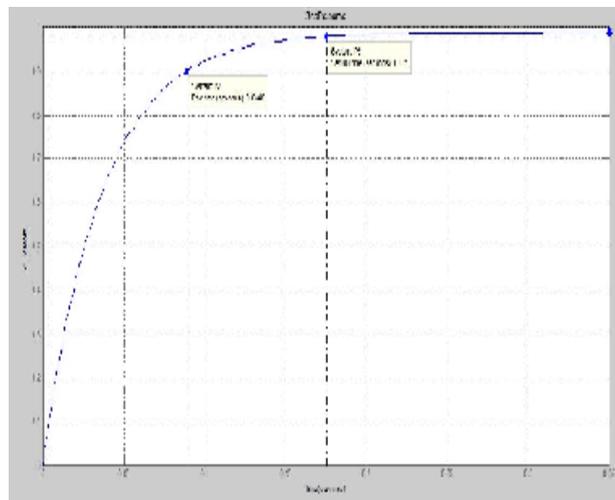


Figure 10 Step Response of GA-PID Controller

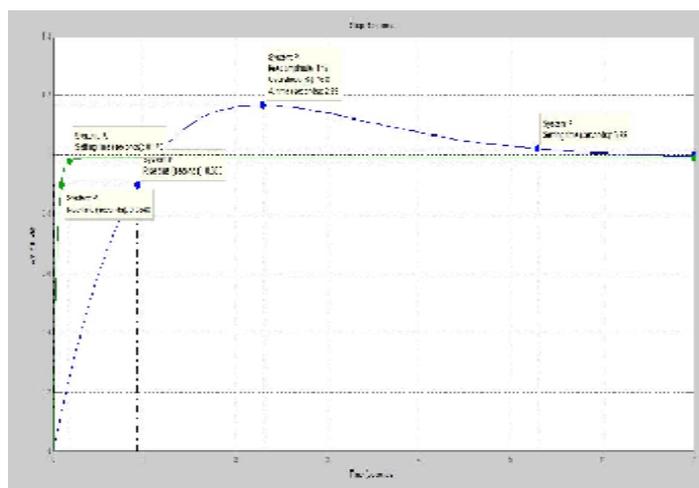


Figure 11 Comparison of Step Responses ZN-PID and GA-PID Controller

V. CONCLUSION

The performance of different controllers is evaluated using transient characteristics (overshoot and settling time) and error indices. The aim of the proposed controller is to regulate the temperature of the outlet process fluid of a shell and tube heat exchanger system to a desired temperature in the shortest possible time and minimum or no overshoot irrespective of step change in load and process disturbances, equipment saturation and non-linearity of different control equipments. After transient analysis carried out on different controllers it is observed that Genetic Algorithms based PID controller provides a satisfactory performance and overcomes the drawbacks of conventional PID controller, feedback plus feed-forward controller. Thus Soft Computing based technique Genetic Algorithms shows 100% improvement in overshoot.

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