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Control of Non-linear Process with Fault Tolerance and Reconfiguration

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Abstract

Controlling of a non-linear process is done by defining the inherent characteristics of a system. In most of the cases with non-linear process, it is highly complicated to control the process with conventional controller. When it comes for stable operating conditions of the process with best performance, a conventional control strategy has to be remodeled and applied. Cascade control is one such approach employed for nonlinear process with time delay as notable constraint. Proportional-Integral-Derivative (PID) controllers suits the control of nonlinear process. Cascade control strategy in series and parallel mode of working and Artificial Neuro Fuzzy Inference Systems (ANFIS) can support in obtaining best results based on stability, optimum performance and better final product outcome. Fault Tolerant Control (FTC) plays a major role in maintaining the process with less or no deviation in the specified operating conditions. Reconfiguration is incorporated based on the above said stability and performance-based working conditions of the process.

Keywords: Nonlinear process, PID controller, series and parallel cascade control, ANFIS, FTC with reconfiguration.

I. Introduction:

In a nonlinear multi input multi output time varying process, stability is a concern which changes based on variations in the operating conditions. While applying controllers to these type of nonlinear process, performance of the process as well as the controller becomes limited. When compared with a linear process, parameters including gain, time constant & dead time will not be constant for the entire operating range [1]. Similarly, for a multivariable process, the complexity of the controller design gets increased. Once the controller is designed, the optimum settings for a controller is tuned based on stability and performance [2]. Cascade control is a mode in which the effects of disturbance are reduced to a greater extent in process where major nonlinearities influence the system with varying performance under different operating conditions. In a series cascade control, disturbance and manipulated variable affects the secondary variable which in turn affect the primary controlled variable. In contrast, disturbance and manipulated variable affects the primary as well as secondary variables simultaneously [3-4]. Controlling the feed flow, composition and tray temperature in a distillation column is a perfect example for this parallel cascade control. Maintaining the overhead product composition and tray temperature is the main objective whereas feed flow is considered to be the disturbance.

II. Literature Survey

Derivation of nonlinear distillation columns was outlined by W.L. Luyben [5]. Parallel cascade control was also initiated by Luyben [6], Yu [7] projected the virtues of cascade control in parallel mode for a nonlinear process. Shen and Yu [8] proposed the methods for selecting secondary measurement parameters for the parallel cascade control. Semino and Brambilla [9] presented the nonlinear filter for improvement of performance in closed loop control and also recognized a combined structure which avoids the interactions between the inner and outer loops. Ogunnaike and ray [10] proposed the multivariable control methods for a pilot plant distillation column. Alina-Simona [11] proposed a model for nonlinear binary distillation column. Rakesh Kumar Mishra, et al [12] has discussed the effects of tuning parameters of a model predictive binary distillation column. G Lloyds Raja, Ahmed Ali [13] discussed the series cascade control and its applications for nonlinear process. Skogestad S [14] proposed the control of a distillation column with dynamic changes. Vinayambika S Bhat et al [15] have implemented the decentralized PI controller for a pilot plant binary distillation column.

Patton, R. J. [16] have addressed the fault tolerant control with its effects for a process, Sulaiman AL., et al [17] discussed about the actuator failures in distillation column and fault tolerant control, Mahmoud, M., et al [18] proposed the stability analysis for a multiple failure process with fault tolerant control. ANFIS based controllers helps in better performance based on time domain specifications compared to other controllers [19].

III. Nonlinear Distillation Process

As mentioned, for a multivariable nonlinear process, stability and performance plays a major role in the operation of the process. This also creates a major impact in the outcome of a process. Consider a nonlinear distillation column which is mostly used in chemical industries for separation process, purification of final products and transfer of energy from one part of the column to the other. It normally consists of trays, reboilers, enriching section, stripping section and condensers, where the interactions between these loops affects the control strategy to a major extent. Decoupling of the interacting loops is also necessary. A wood and berry model distillation is taken for analysis of the product composition as well as temperature. Figure 1 represents the distillation column model.

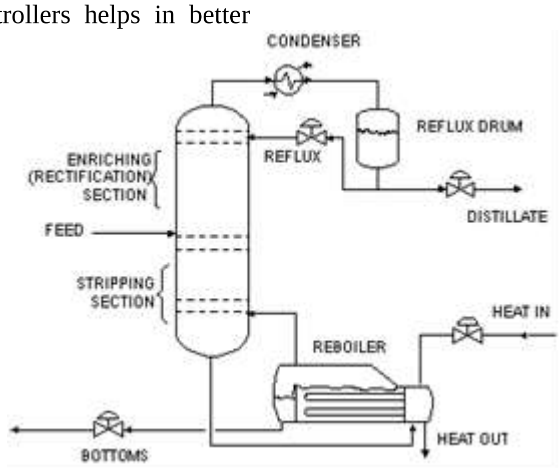

Fig 1: Distillation Column

In this paper, material balance control and product quality control are taken into consideration. Inflow to the column is considered for the material balance control. The impact of flow will be direct on temperature and level of the column. This application is preferred for flow and temperature measurements. When coming to the controller part, a decentralized controller is better for a multivariable process, but interactions in the process variables affect the performance of the column. Due to this, product composition in the top and bottom tray gets affected. With these constraints, selecting a suitable controller which ensures the stability and performance of the column, cascade control technique becomes a better choice.

IV. Control Technique

PID Controller is used for controlling most of the industrial processes. This combinational controller has the cumulative advantages such as reducing the errors, maintaining the integral time, eliminating the offset value and also helps in increasing the performance & stability of the process under control.

Control techniques such as feedback, feed-forward, ratio, split range and cascade are used for controlling nonlinear process. As cascade control technique is concerned, there are two loops named as primary or outer loop and secondary or inner loop are available. The inner loop controller output normally controls the outer loop process.

There are two major types of cascade control stated as series cascade control and parallel cascade control. As the name implies, in series cascade control the disturbance act on the primary as well as secondary loop in series manner.

,It should be noted clearly that the series and parallel cascade control is arbitrated with the characteristics of the process and not based on the control system for a process. Series cascade control finds its application where traditional unity feedback control fails to eliminate the load disturbances before the deviation of controlled variable from the set value. Figure 2 denotes the generalized block diagram of a series cascade control.

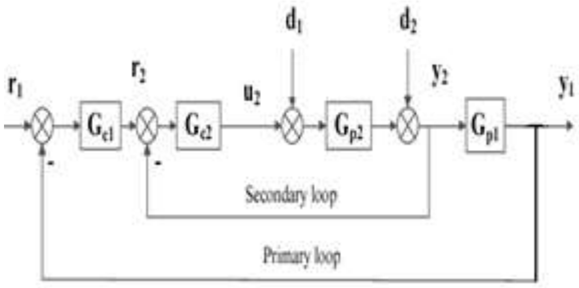

Fig 2: Block diagram of series cascade control

Transfer functions of the primary and secondary loop process are named as G_{p1}, G_{p2} whereas controllers of primary and secondary loops are named as G_{c1}, G_{c2}. Set value of inner and outer loops are denoted as r_2 and r_1. The output of inner loop controller is represented as u_2, inner loop process as y_2 and outer loop process as y_1.

$G_{p1}=\frac{K1e-\theta 1s}{\tau 1s+1}$, $G_{p2}=\frac{K2e-\theta 2s}{\tau 2s+1}$

Considering the above standard transfer function, simulation has been done in series mode and parallel cascade mode with conventional PID controller and ANFIS controller. Series cascade control can be effective only when the working of secondary loop is much faster than the primary loop. Also, the disturbances that enter the process is higher at the secondary loop. Simulation diagram of a series cascade control for a distillation process is shown in figure 3.

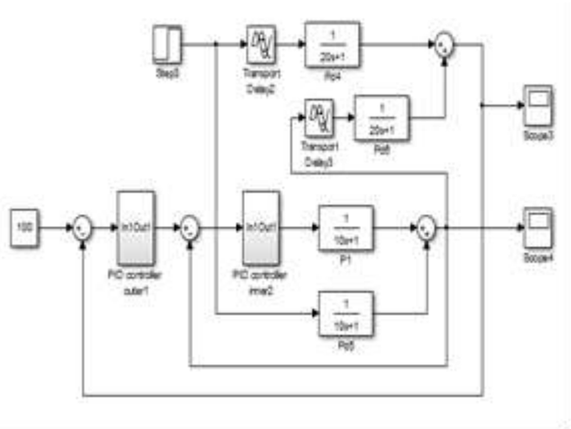
Fig 3: Simulation model of series cascade control of a distillation column

The above model represents the series cascade control where disturbance at the primary and secondary loops affect the process in series manner. Figure 4 shows the inner and outer loop responses of a series cascade control for a distillation column.

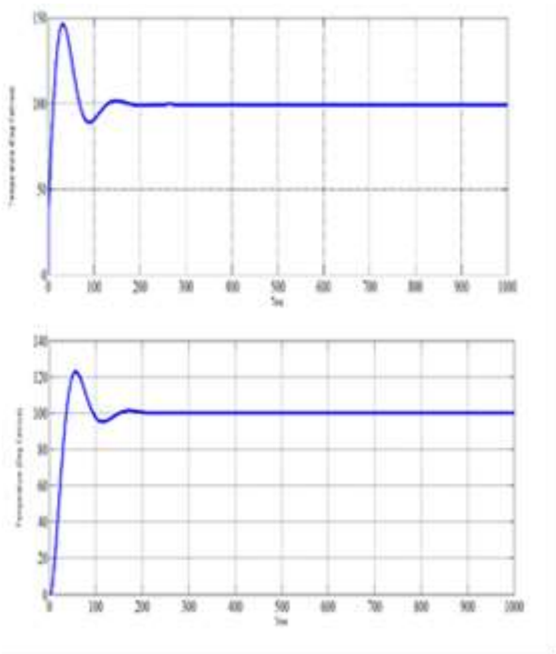

Fig 4: Inner and outer loop responses of series cascade control

In the case of parallel cascade control, manipulated variable and disturbances act on the inner and outer loop outputs in parallel means. Rejection of disturbances is the major concern while dealing with multivariable process. If we design a separate controller for both variables, then complexity of controller design gets increased. To avoid this kind of complexity, parallel cascade control is being applied. Figure 5 presents the block diagram of a parallel cascade control.

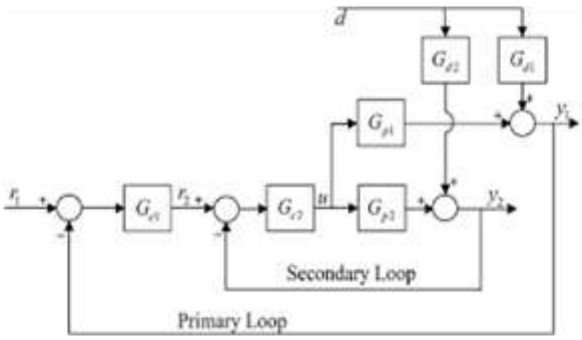

Fig 5: Block diagram of parallel cascade control

In parallel cascade control, diagram represents the act of disturbance with the inner and outer loop in parallel means. The inner and outer loop responses for parallel cascade control of distillation column is represented in figure 7.

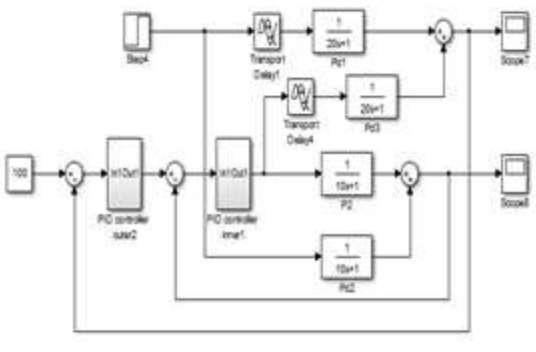

Fig 6: Simulation model of parallel cascade control of a distillation column

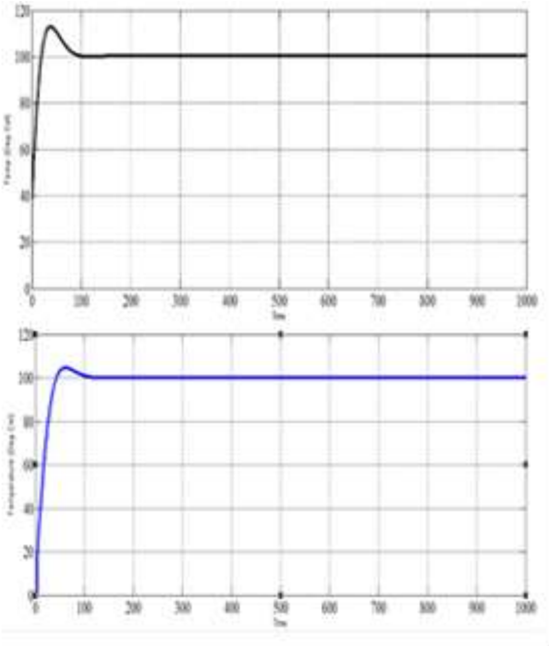

Fig 7: Inner and outer loop responses of parallel cascade control

Considering a different state in the process with identical dynamics, we have also analysed the series and parallel cascade structures for a distillation column. The response of series and parallel cascade control structures were presented for a different case with disturbances in the primary and secondary loops when the time delay is excluded corresponding to the delay in primary output.

Setpoint tracking is better in parallel cascade control and load disturbances gets controlled without deviating the output. Faults that occur in the working of a distillation column are mainly accounted since it affects the stability and performance of the column. The output response for inner and outer loop of a series cascade control for time delay excepted model is presented in figure 8 with the new composition in distillation column. Similarly, response of inner and outer loop in parallel cascade control is presented in figure 9.

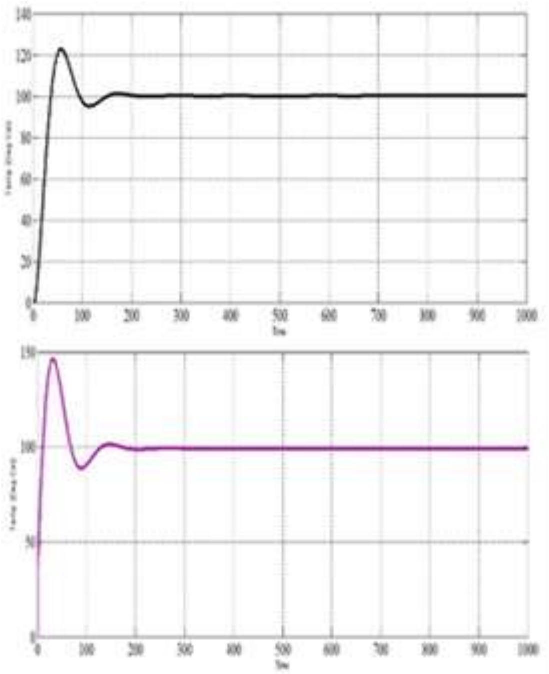

Fig 8: Response of outer and inner loop with series cascade control for time delay excepted model

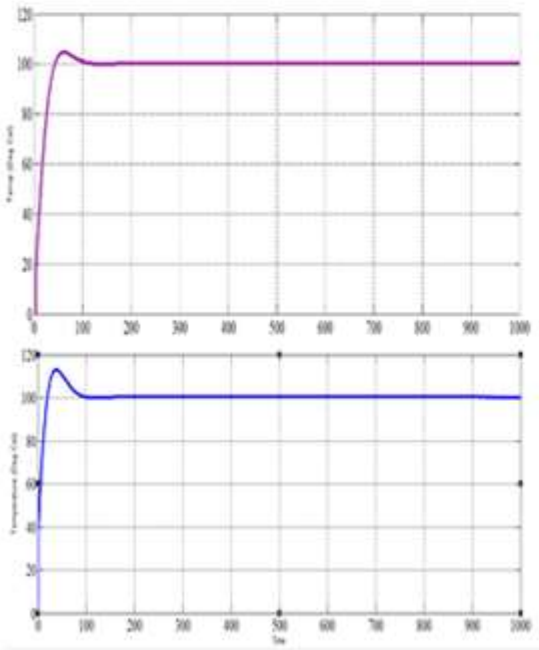

Fig 9: Response of outer and inner loop with parallel cascade control for time delay excepted model

ANFIS controller design and simulation:
ANFIS construction includes input-output mapping with design of fuzzy based if-then rules and human knowledge. Conventional neural networks use approximate functions from numerical input-output data. Fuzzy-neural networks are more general computational structure with which function approximation can be extended to linguistic data[29]. To illustrate the use of neural networks for fuzzy inference, consider a fuzzy rule base consisting of Takagi-Sugeno if-then-else rules. ANFIS architecture is shown in the figure below where inputs x and y are provided to the activation layers and based on the bias condition provided, output gets processed with the neural and fuzzy inference system. Backpropagation learning algorithm is adopted for the ANFIS structure.

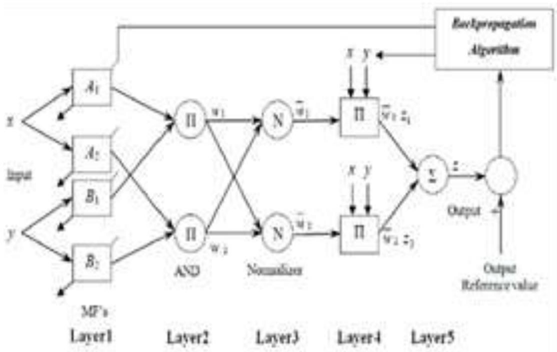

Fig: 10 ANFIS architecture

In ANFIS, the membership functions associated with the parameters and tuning rules are always modified based on the training data and learning procedure[28]. ANFIS is a data processing method and it is more important to keep the data in sufficient operating range with input and output variables of the plant. In the architecture, layer 1 provides the input defuzzification membership functions and layer 2 deals with the activation functions. Layer 3 establishes the links with normalizing function and layer 4 refers to the functions corresponding to the inputs. Layer 5 provides the output and feedback connection.

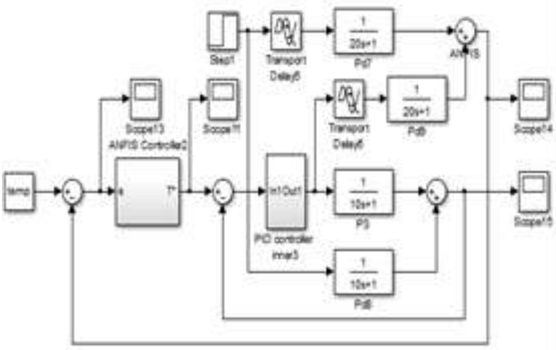

Fig: 11 MATLAB Simulation with ANFIS controller

In Takagi-Sugeno model, output of each rule is based on the linear combination of input variables and a constant term. Weighted average of individual rule output is obtained as the final output and the weights of the functions are determined using training algorithm. Objective of the training algorithm is to determine the best value for the premise and consequent parameters in order to make the ANFIS output match with the desired value.

Typical Taksgi-Sugeno Rule base is provided for the given ANFIS structure as follows.

Rule 1: If x is A1 and y is B1, then, h1=w1x+z1y+r

Rule 2: If x is A2 and y is B2, then, h2=w2x+z2y+r

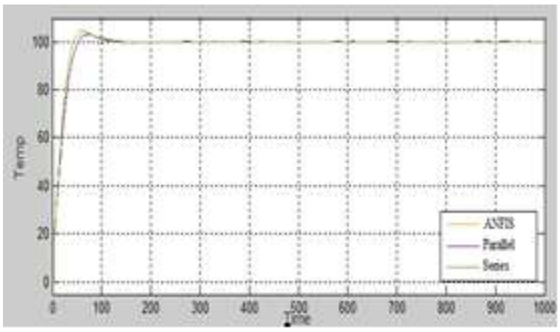

Fig 12: Response of ANFIS controller

Backpropagation network is used for increasing the speed of convergence with an adaptive learning rule. Above responses shows that the performance is better in ANFIS with respect to the time domain specifications. Error value gets reduced and the column dynamics in steady state is achieved with respect to the peak overshoot and oscillations were not present. Stabilizing of composition profiles can be achieved using these controllers, leading to an effective control of the column.

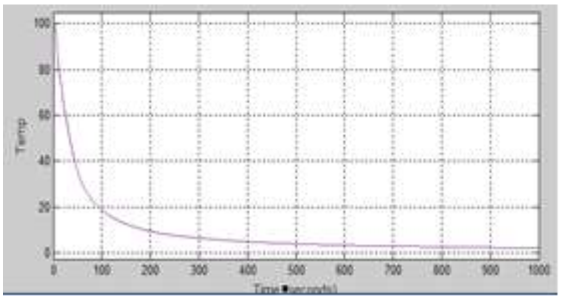

Fig 13: ITAE output with ANFIS controller

V. Fault Tolerant Control and Reconfiguration

For a safe and reliable operation of a distillation column, it is most important to account the faults that occur in the sensors and actuators. Reconfigurable or fault tolerant controller is the part of a fault tolerant control system which helps in detecting the fault at the early stage and also to maintain the fault in an acceptable range until the fault is rectified. Faults that occur in the column are detected by fault detection and diagnosis scheme. Faults that were detected are controlled by reconfigurable controllers.

In this fault tolerant control system, a fault or disturbance is considered to be the feed flow rate with a minor struck (dead time) for the control valve. This affects the response of the system to an extent which can be controlled by a bypass actuator which opens for instant. At the same time, PID controller acts as a reconfigurable controller for eliminating the fault occurred in the column. This is possible by means of providing a reference value to the controller based on the typical operating conditions.

Modelling of distillation column depends on the operating cost, product income and energy efficient usage. Design of effective control system for a column is a major concern with cost normalization. Increase in temperature feed and reboiler design is concerned with the operating cost. High purity distillation column consumes more energy and the cost of operating the column gets higher.

VI. Simulation Results and Discussion

Tuning of the PID controller is performed by using Zeigler-Nicholas method in series and parallel cascade loops and controller values were obtained. The responses of inner and outer loop in series cascade and parallel cascade control were presented. ANFIS has been implemented and the controller values were obtained using the learning algorithm and Takagi-Sugeno model. Based on the response, ANFIS output looks better in terms of reduction in maximum overshoot. Also, settling time for the process is also less when compared to the series and parallel cascade control.

Control technique	Overshoot (M_P %)		Rise time (t_r) Sec		Settling time (t_s) Sec	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Series	20%	25%	58	62	230	235
Parallel	4 %	5 %	36	38	120	130
ANFIS controller	2 %	3 %	12	16	110	120

Based on the above responses and comparison table, ANFIS is better in terms of settling time and minimum overshoot. ITAE is also reduced to a greater extent as the response is shown in figure 13. ITAE is directly linked with operating cost and energy consumption while working with the column. In this case a minimum change/reduction in the error component will produce an impact in the above parameters at high level.

VII. Conclusion

The comparison table reflects that ANFIS has better improvement in the performance of a process than series and parallel cascade mode of control. Same time, stability is also good when compared to the former technique. Apart from these factors, the advantage of minimal interactions in loops is also possible which helps in designing decouplers. While considering Integral Time Absolute Error, the percentage of reduction in error is better in the case of ANFIS when compared with series and cascade modes. Cost of design and operating the distillation column is accounted where nominal reduction will be there in cost factor with ANFIS since the effect of disturbance is controlled and energy consumption gets reduced.

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