Improving Transient Response and Reducing the Effects of Perturbations on Isotope Separation Plants Using a Neuro-Fuzzy Controller

MARTIN KAUCSÁR*, DAMIAN AXENTE, VIOREL COSMA, AUREL BÂLDEA
National Institute for Research and Development of Isotopic and Molecular Technologies, 65-103 Donath Str.,400293, Cluj-Napoca, Romania

In developing control systems for isotope separation plants, in order to increase the separation efficiency, amongst the most important tasks are: the minimization of the transient response and the reduction of disturbances effects over the process. In order to fulfill these requirements we develop a neuro-fuzzy feedforward control configuration. Process determining parameters are controlled by using a multiloop control scheme, in each control loop being identified: a feedback loop and a feedforward loop. In the first case the controlled parameter is compared with its setpoint, and if there is a deviation, the feedback controller, based on fuzzy-logic, takes action according to the control strategy. The feedforward controllers are implemented by a neuro-fuzzy model. The parameters of a feedforward fuzzy control system are inherently difficult to tune for the purpose of improving the control requirements. This drawback is resolved by integrating the learning and computational power of neural networks into fuzzy systems. The feedforward controller learns the inverse of the plant process to give at the output of the feedforward loop the input to the plant process needed to follow the desired setpoint.

Keywords: chemical process control, feed-forward, fuzzy logic, ^{15}N separation plant

The control system, presented in this paper, is dedicated to maintain automatically the process of ^{15}N separation, by chemical exchange in Nitrox system, in its optimal operation conditions. For this purpose one of the most important task is: the minimization of the transient response and of the disturbances effects over the process. These requirements are fulfilled by applying a neuro-fuzzy feed-forward control configuration.

Fuzzy logic control systems have been successfully applied to a wide variety of practical problems. The fuzzy systems have three significant advantages over conventional control techniques. They are cheaper to develop, cover a wider range of operating conditions, and are more flexible in terms of natural language. Unfortunately the parameters of a fuzzy control system are inherently difficult to tune for the purpose of improving behavior [1]. This drawback is overcome using neural networks. Artificial neural networks offer the advantage of performance improvement through learning by means of parallel and distributed processing. The parameters of the feed-forward controller are tuned using a neural network.

By integrating neural networks in fuzzy systems a new class of control systems results: – intelligent control systems. Intelligent control is a technology that replaces the human mind in making decisions, planning control strategies, and learning new functions whenever the environment does not allow or does not justify the presence of a human operator. The use of intelligent control systems has infiltrated the modern world. Specific features of intelligent control include decision making, adaptation to uncertain media, self-organization, planning and scheduling operations. Very often, no preferred mathematical model is presumed in the problem formulation, and information is presented in a descriptive manner. Therefore, it may be the most effective way to solve complex control tasks of chemical plants.

General Architecture of the Control System

The developed control system uses two controllers: feedback controller and feed-forward controller (fig. 1) [2, 3]. The actuating control signal results by summing the outputs of these controllers:

$$u = u_{FB} + u_{FF} \quad (1)$$

The feedback controller, placed in the feedback loop, compares the process output y with the reference input r, and if there is a deviation e = r - y, the controller takes action according to the control strategy. The feedforward controller placed in the feed-forward loop reduces the transient response and compensates all measurable disturbances.

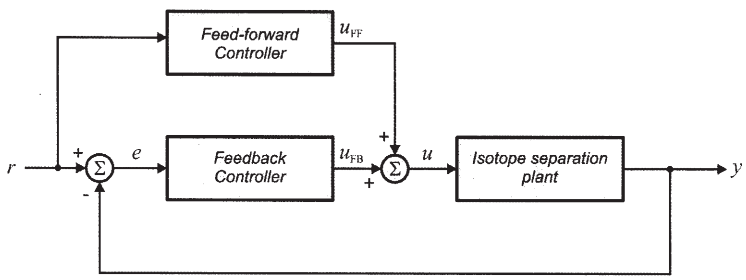

Fig. 1. General configuration of the ^{15}N isotope separation plant control system

* email: kaucsar@itim-cj.ro; Tel.: +40 264 584037

The transient response improvement is analyzed using the block diagram from figure 2, where, for clarity, the feedback loop is omitted [4]. The transfer function of the chain, formed by cascading the feed-forward controller and plant, is:

$$G(s)=\frac{y(s)}{r(s)}, \quad \text{or} \quad G(s)=G_{FF}(s)\cdot G_P(s) \qquad (2)$$

If $y(s) = r(s)$ then the controlled output follows rigorously the reference input. Accordingly from the relation (2) results:

$$G_{FF}(s)=\frac{1}{G_P(s)} \qquad (3)$$

Knowing the transfer function of the controlled process:

$$G_P(s)=\frac{y(s)}{u(s)} \qquad (4)$$

and using the relation (3), can be obtained the response improving transfer function:

$$G_{FF}(s)=\frac{u(s)}{y(s)}, \quad \text{that is:} \quad G_{FF}(s)=G_P^{-1}(s) \qquad (5)$$

This means that the quality of the feed-forward control is dependent on the accuracy of the inverse model of the controlled process.

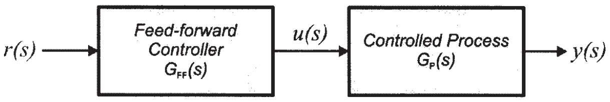

Fig. 2. Signal flow in feed-forward path

The feed-forward controller can compensate known and measurable kinds of disturbances. This is analyzed using the block diagram from figure 3, where the feedback loop is omitted. The process output $y(s)$ is given by a sum of two components:

$$y(s)=y_D(s)+y_P(s) \qquad (6)$$

where $y_D(s)$ – the process output corresponding to the actuating control input $u(s)$, and $y_p(s)$ – the unwanted process response to the disturbance $d(s)$. Taking into consideration the corresponding transfer functions, results:

$$y(s)=G_D(s)\cdot d(s)+G_{FD}(s)G_P(s)\cdot d(s) \qquad (7)$$

In order to compensate the known and measurable disturbances must have: $y(s)=0$. Wherefrom the transfer function of the feed-forward controller is:

$$G_{FD}(s)=-\frac{G_D(s)}{G_P(s)} \qquad (8)$$

In table 1 are summarized the advantages and drawbacks of the feed-forward and feedback controllers. Combining them in this control system all advantages are provided.

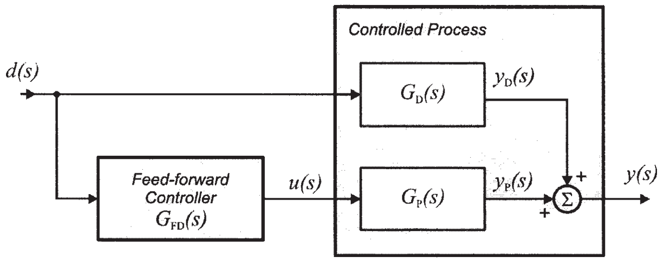

Fig. 3. Disturbance compensation using a feed-forward controller

The isotope separation processes are complex and nonlinear. If a nonlinear plant changes operating point, it may be possible to change the parameters of the controller according to each operating point. This is called gain scheduling adaptive control since it was originally used to change process gains. A gain scheduling adaptive controller contains a linear controller whose parameters are changed as a function of the operating point in a preprogrammed way. It requires thorough knowledge of the plant, but it is often a good way to compensate for nonlinearities and parameter variations. Sensor measurements are used as scheduling variables that govern the change of the controller parameters, often by means of a table look-up. The gain scheduling adaptive fuzzy feed-forward control scheme is shown in figure 4. The feed-forward controller is implemented by a neuro-fuzzy model which learns the inverse of the process in order to give as output of the feed-forward loop, once trained, the input to the process needed to follow the desired setpoint trajectory. Instead of specifying the desired control output for a given process state, the inverse fuzzy process model predicts the process output to be expected in the future, due to the current and previous process states and control outputs [5, 6].

The following relations describe the behavior of this system in quasi-linear operating mode. All functions are in (s) plane. The following notations are used: G_p – transfer function of the controlled process, corresponding to the actuating control signal u, G_{Dm} – transfer function of the controlled process, corresponding to measurable

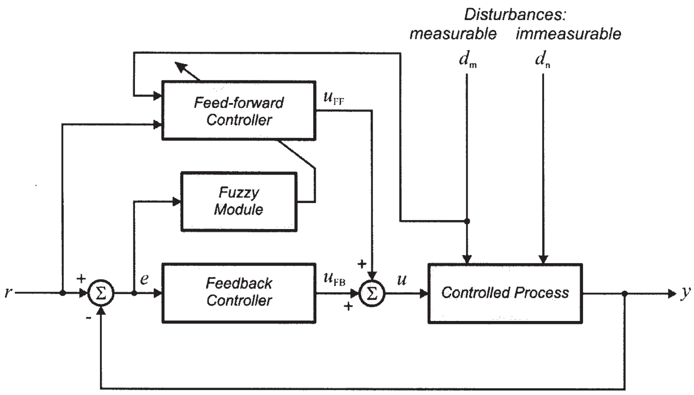

Fig. 4. Adaptive neuro-fuzzy controller with two control loops

Table 1
THE ADVANTAGES AND DRAWBACKS OF THE FEED-FORWARD AND FEEDBACK CONTROLLERS

	Feed-forward	Feedback
Advantages	• Compensates for disturbance before controlled variable is affected • Does not affect the stability of the control system	• Provides zero steady state offset • Effective for all disturbances
Drawbacks	• Cannot eliminate steady state offset • Requires a sensor and model for each disturbance	• Does not take control action until the controlled variable deviates from its set point • Affects the stability of the control system.

disturbance d_m, and G_{Dn} – transfer function of the controlled process, corresponding to immeasurable disturbance d_n. Taking into consideration the relation (1) and the expression of the transfer functions, the process output signal becomes:

$$y = G_P (u_{FB} + u_{FF}) + (G_{Dm}\, d_m + G_{Dn}\, d_n) \qquad (9)$$

The output signal delivered by the feedback and by the feed-forward controller is:

$$u_{FB} = G_{FB} (r - y) \qquad (10)$$

and respectively:

$$u_{FF} = G_{FR}\, r + G_{FD}\, d_m \qquad (11)$$

where G_{FB} – transfer function of the feedback controller, G_{FR} – transfer function of the feedback controller, corresponding to the reference input r, and G_{FD} – transfer function of the feedback controller, corresponding to the measured disturbance d_m. Replacing the expression of process control signals obtained from (10) and (11) in (9) results:

$$y = \frac{G_P\, G_{FB} + G_P\, G_{FR}}{1 + G_P\, G_{FB}} \cdot r + \frac{G_P\, G_{FD} + G_{Dm}}{1 + G_P\, G_{FB}} \cdot d_m + \frac{G_{Dn}}{1 + G_P\, G_{FB}} \cdot d_n \qquad (12)$$

The relations (5) and (8), with the above used notations can be written as:

$$G_{FR} = G_P^{\ -1}, \qquad G_{FD} = -\frac{G_{Dm}}{G_P} \qquad (13)$$

and, introducing the relations (13) in (12), results:

$$y = r + \frac{G_{Dn}}{1 + G_P\, G_{FB}} \cdot d_n \qquad (14)$$

Consequently, if the transfer functions of the feed-forward controller satisfies the relations (13), then the controlled output follows the input reference, and the measured disturbances are compensated. The effect of unmeasured disturbances will be reduced with G_P, G_{FB}, that is with the gain of the feedback controller.

Refluxer reaction zone control with feed-forward controller

In the product refluxer of the [15]N separation plant exothermal chemical reactions take place in a 10 - 20 cm height reaction zone:

$$\begin{aligned} &2HNO_3 + 3SO_2 + 2H_2O \rightarrow 2NO + 3H_2SO_4 \\ &2HNO_3 + SO_2 \rightarrow 2NO_2 + H_2SO_4 \end{aligned} \qquad (15)$$

For optimal operation of the separation column this reaction zone must be maintained in the product refluxer at a given position [1], which is localized by determining the peak of the temperature gradient measured along the refluxer. Hence the refluxer is provided by a temperature sensor array (fig. 5). The temperature information is processed to find the position and the height of the temperature gradient peak [7].

The position of the reaction zone is a function of the following parameters: L_C – nitric acid flow-rate, G – sulphur dioxide flow-rate, L – cooling water flow-rate, T_A – surrounding ambient temperature, and the nonuniform distribution of the flow-rates in the refluxer sections due to deviations from uniformity of the packing. It is obvious that the flow-rate of the nitric acid and of the sulphur dioxide is determinative to the position of reaction zone. Therefore this is controlled by the flow-rate of the sulphur dioxide, while the flow-rates of the nitric acid and of the cooling water are maintained at a nearly constant level, using constant flow feeding pumps.

The desired controlled value of sulphur dioxide flow-rate is obtained by adding two components: G_P – primary flow-rate and G_A – additional flow-rate. Feeding the refluxer only with the primary flow G_P the reaction zone falls near of its optimal position, but slightly down. To get the optimal position over the primary flow is switched the additional flow G_P:

$$G = G_P + \alpha \cdot G_A \qquad (16)$$

where α is 0 or 1 function of the switching sequence. Switching with delta-sigma modulation the mean value of the sulphur dioxide flow-rate follows quickly the actuating value [8]. The modulation algorithm is shown in figure 6.

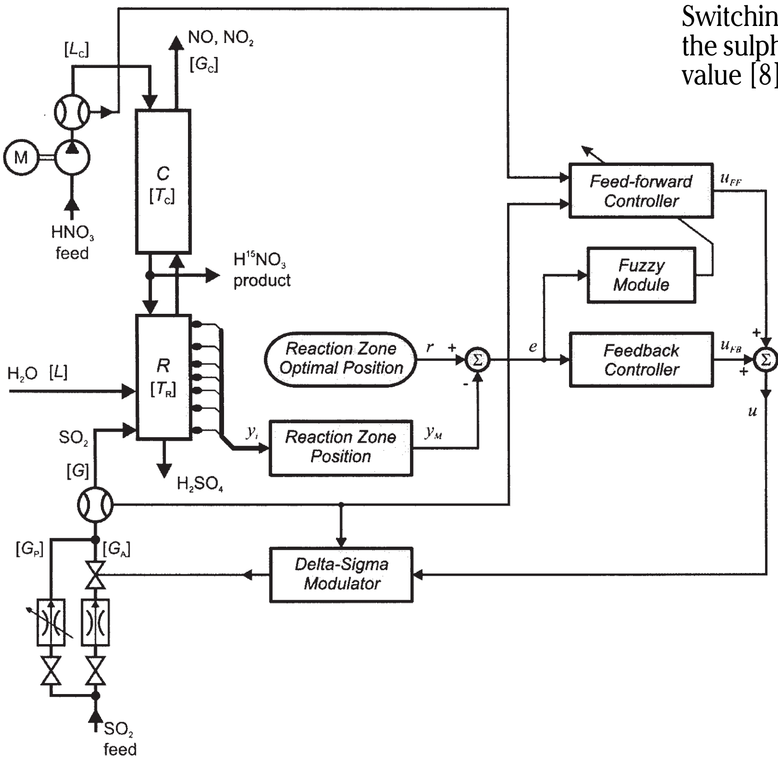

Fig. 5. Reaction zone control using a feed-forward controller

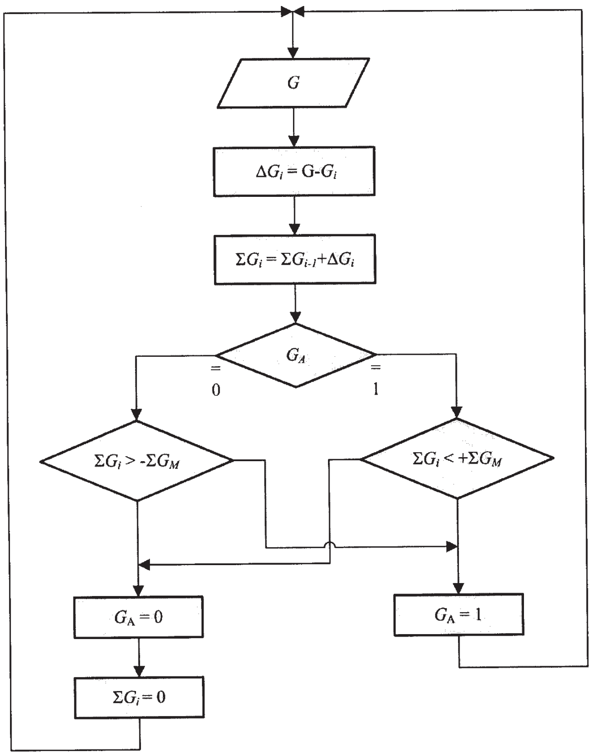

Fig. 6. Delta-sigma modulation algorithm for sulphur dioxide flow control

The short term deviations of the nitric acid flow-rate from its optimal level L_C, and the short term deviations of the sulphur dioxide from the predefined G_P and G_A flow-rates constitutes measurable disturbances. The feed-forward controller compensates these deviations. Between nitric acid and sulphur dioxide flow-rate is a linear dependency:

$$G = k L_C + G_0 \tag{17}$$

This dependence is experimentally proven and, for the refluxer of the second separation column [1], the following values: = 6.8972 L/h and k = 277.79 have been measured. The fuzzy module evaluates the value of G_0 and k in order to adapt the transfer function of the feed-forward controller to the corresponding refluxer.

The influence of the ambient temperature is eliminated by the reaction zone position processing module. The influence of the cooling water flow-rate and of the not uniform flow-rate distribution onto the position of the reaction zone is almost eliminated by the high gain of the feedback controller.

Conclusion

The control system is developed for ^{15}N separation plant, in order to increase the separation efficiency. In this context the most important tasks are: the minimization of the transient response and the reduction of disturbances effects over the process. In order to fulfill these requirements a neuro-fuzzy feed-forward control configuration is used. Process determining parameters are controlled by using a multiloop control scheme, in each control loop being identified: a feedback loop and a feed-forward loop. The feed-forward controller without affecting the stability of the control system improves the transient behaviour of the plant and compensates the measurable disturbances before controlled variable is affected. The feedback controller provides zero steady state offset and is effective for all disturbances. The system being adaptive, the parameters of the feed-forward controller are tuned using a neural network.

The short response for the actuating signal is assured by switching the sulphur dioxide flow control valve using a delta-sigma modulator.

References

1. KAUCSÁR, M., AXENTE, D., COSMA, V. BÂLDEA, A., Rev. Chim.(Bucharest), **58**, no. 8, 2007, p. 809.
2. BRANDIZZI, J., SANTOS, M., DEXTER, A.L., Commissioning an adaptive fuzzy control scheme, Department of Engineering Science University of Oxford; Proc. 6th UK Workshop on Fuzzy Systems Brunel University, Uxbridge, p.125.
3. ABONYI, J., NAGY, L., SZEIFERT, F., Adaptive Fuzzy Control to Compensate Process Nonlinearities, University of Veszprém, Dept. of Chem. Eng. Cybernetics; Chemical Engineering Research and Design, 77, A, 281-290, 1999, IF 0.686
4. ABONYI, J., NAGY, L., SZEIFERT, F., Adaptive Sugeno Fuzzy Control: A Case Study, University of Veszprém, Dept. of Chem. Eng. Cybernetics; Advances in Soft Computing: Engineering Design and Manufacturing (Lecture Notes in Control and Information Sciences, Vol) by R. Roy (Editor), T. Furuhashi (Editor), P. K. Chawdhry (Editor), M. Ruggieri (Editor), Chawdrhy, Springer Verlag; May 1999.
5. ZAHARIE, D., Calcul neuronal şi calcul evolutiv, Rezolvarea problemelor de asociere cu reţele neuronale feedforward, Universitatea de Vest, Timişoara, Facultatea de Matematică şi Informatică, Departamentul de Informatică, 2005.
6. GUPTA, M.M., JIN, L., HOMMA, N., Static and Dynamic Neural Networks, From Fundamentals to Advanced Theory, John Wiley & Sons, Inc., Hoboken, New Jersey, 2003.
7. KAUCSÁR, M., COSMA, V., AXENTE, D., BÂLDEA, A., POPESCU, ST., DOBOCAN, I., ZOTOIU, D., 4th Conference "Isotopic and Molecular Processes" Studia Universitatis Babeş-Bolyai, Physica, 5, 4a, 2005, p.395.
8. ZRILIC, D. G., Circuits and Systems Based on Delta Modulation Linear, Nonlinear and Mixed Mode Processing, Springer, 2005, XV, ISBN: 978-3-540-23751-8, p.20

Manuscript received: 23.07.2009